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This volume of the Journal of the Entomological Society of Ontario marks many transitions, and the beginnings of some new directions. This volume of JESO was co-edited by Yves Prévost, outgoing editor, and myself. I sincerely thank Yves for all the work he has put in as JESO Editor over the last few years and also for helping me to learn how to guide manuscripts through the review process and eventually to publication. I would have been pleased to thank Yves a year ago had I written the Editor's message for the previous volume – but my appreciation of his work and effort has grown all the more for having experienced the job at first hand.

I also wish to thank JESO's Editorial Board, some of whom are new to the job, and some of whom are old hands: Andy Bennett, Neil Carter, Dolf Harmsen, Yves Mauffette, and Jeff Skevington. Their scientific understanding and editorial skills ensure the scientific quality of our Journal and have helped me enormously as I learn this new job. Our new Technical Editor, Amy Rutgers-Kelly, has the job of transforming the manuscripts into final, print-ready format.

This brings me to another set of transitions, and to my major goals as Editor of the Journal. I believe that electronic publishing is critical to the survival of the Journal. Volume 136 marks our transition to completely electronic submission and manuscript processing. This is an important shift in the production of the Journal and is the first step in the transition to electronic publication. For the first time, authors of papers in the current volume will receive a pdf version of their papers so that they may distribute them electronically. The next step will be electronic publication of the Journal, in addition to paper publication. When we have achieved this goal, then JESO will become available to a much wider entomological audience than is currently possible with paper distribution only. However, in order for our authors' work to reach the audience it deserves, we also need to be listed by electronic journal listings services. In this age of electronic database searches, articles can be overlooked if their journals are not listed (the JESO Editor herself has failed to find articles published before her time in JESO!). In order to be included in these listings, JESO must commit to a regular publication schedule. To do this we intend to first close the gap between volume year and actual publication year; this should be accomplished by 2007.

Finally, it is my pleasure to introduce the contents of V136, which cover the entomological gamut from taxonomy to ecology to applied entomology, each study focusing on a different order - from wasps and bees, to flies, thrips, beetles, moths, aphids, and even mites. I hope that the scientific quality of these papers and their readability will encourage all our readers to consider submission for publication in future issues of JESO.

Happy reading!

Miriam H. Richards
Editor

JOURNAL

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VOLUME 136

GROUND BEETLES (COLEOPTERA: CARABIDAE) FROM ALVAR HABITATS IN ONTARIO

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Abstract

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An inventory of ground beetles (Coleoptera: Carabidae) was conducted in ten alvar sites, representing four alvar types, in southern Ontario. We identified 142 species from 8647 specimens. Species richness and numbers of specimens were generally higher in alvar grasslands. Alvar pavement and alvar shrubland generally had lower species richness and specimen numbers. Each site had between four and seven dominant (over 5% of individuals collected at the site) species, which varied between alvar types and localities. Three of the dominant species (*Agonum nutans*, *Chlaenius purpuricollis,* and *Pterostichus novus*) have rarely been collected in non-alvar sites in the region. Most of the species collected are associated with open habitats or grassy meadows. The carabid fauna collected was dominated by widespread or eastern North American species, although some northern and southern species were near the limits of their range. The known distribution of *Cicindela denikei* was extended eastward from northwestern Ontario. Nine introduced European species were collected, and only two (*Carabus nemoralis* and *Pterostichus melanarius*) were dominant at any site.

Introduction

Alvars are naturally open areas of thin soil overlying flat limestone or dolostone. The vegetation is generally sparse and dominated by grasses (Poaceae), sedges (Cyperaceae), and shrubs. Trees are rare because there are few areas with sufficient soil accumulation. Six types of alvars are recognized based on the percentage of exposed bedrock, herb and shrub cover, and tree cover (Catling and Brownell 1995). North American alvars are concentrated in the Great Lakes region, where the limestone was denuded by glaciation and the sites have been maintained as natural openings by multiple factors including fires, grazing by large herbivores, lack of soil, and a seasonal pattern of flood-drought-flood in spring, summer, and fall, respectively. There are 250 to 300 known alvar sites in the Great Lakes region,

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mostly in southern Ontario, but also in New York, Michigan, Ohio, Quebec, and Vermont (Catling and Brownell 1995; Reschke et al. 1999).

The flora of alvars is well known: 347 species of native plants have been identified in Great Lakes alvars, of which 28% are considered characteristic of alvars. There are also several endemic species. The lack of introduced European flora is notable, although many of these species have invaded alvars recently because of artificial or man-made stresses. Due to the combination of present conditions (geology, hydrology, etc.) and postglacial history of alvars, plant species with northern, western, and southern Nearctic affinities coexist in these sites (Catling and Brownell 1995).

Surveys of arthropods in North American alvars have been sporadic compared to surveys in Europe. Approximately 1800 species of arthropods, including more than 700 species of Coleoptera, have been recorded in the Great alvar of Öland (Sweden) alone (Lundberg 1983; Coulianos and Sylvén 1983). As for North America, Catling and Brownell (1995) documented a number of rarely collected species of Lepidoptera, Coleoptera, and Hymenoptera in Ontario alvars. There are also 18 species of leafhoppers (Hemiptera: Auchenorrhyncha) occurring in Great Lakes alvars that are normally associated with prairie habitats (Bouchard et al. 2001). Bouchard et al. (1998) provided phenology and habitat data on three species of Carabidae (Coleoptera) that are abundant in Ontario alvars but rarely collected elsewhere in Ontario.

As part of the International Alvar Conservation Initiative (Reschke et al. 1999), the objective of this study was to conduct a faunal inventory of the ground beetles (Coleoptera: Carabidae) in southern Ontario alvars to provide baseline data on the species and communities in this unique ecosystem.

Methods

Ten sites, representing four alvar types (pavement, shrubland, savanna grassland, grassland) were sampled in southern Ontario in 1996-1997 (Table 1). Sample sites were described and mapped in Bouchard et al. (1998; 2001). Examples of each alvar type are shown in Figure 1.

Sampling methods at each site consisted of one Malaise trap, 16 uncovered pitfall traps (white plastic beer cups, 9 cm in diameter), 16 pan traps (355 ml yellow plastic bowls, 15 cm in diameter), and two flight intercept traps, distributed randomly throughout the site. Pan traps and pitfall traps were set with their upper rim flush with the ground surface, which in alvars with thin soil cover restricted their use to cracks in the bedrock. Propylene glycol or ethylene glycol was used as the preserving fluid and a drop of liquid detergent or Kodak Photoflo® was added as a wetting agent. All traps were serviced twice a month and specimens were preserved in 70% ethanol prior to mounting. Hand collecting and sweeping were used to supplement trap catches at every visit to the sites. All traps operated from mid-May until mid-September. At Site 9, small mammals disturbed the pitfall traps and pan traps frequently throughout the summer. Although the data from this site were included in the species list and calculation of overall numbers of beetles, the site was omitted from the calculation of dominant species and rarefied estimates of species richness.

In order to determine whether certain species of carabids were characteristic of

TABLE 1. Location of study sites in Ontario alvars.

Site	Location	Alvar region	Coordinates	Alvar type	Sampling
1	Misery Bay Prov. Nat. Res.	Manitoulin Island	N 45°47'26" W 082°45'00"	alvar pavement	June - Sept 1996
2	10 km W Evansville	Manitoulin Island	N 45°49'18" W 082°41'04"	alvar shrubland	June - Sept 1996
3	10 km SW Gore Bay	Manitoulin Island	N 45°52'12" W 082°31'48"	alvar savanna grassland	June - Sept 1996
4	10 km W Gore Bay	Manitoulin Island	N 45°53'45" W 082°34'41"	alvar grassland	June - Sept 1996
5	5 km E Camden East	Napanee Plain	N 44°20'19" W 076°47'49"	alvar grassland	June - Sept 1997
6	3 km N Miller Lake	Bruce Peninsula	N 45°07'46" W 081°26'44"	alvar pavement	June - Sept 1997
7	Cabot Head	Bruce Peninsula	N 45°14'44" W 081°18'28"	alvar grassland	June - Sept 1997
8	1.5 km NE Dalrymple	Carden Plain	N 44°41'02" W 079°05'31"	alvar grassland	June - Sept 1997
9	7.5 km E Seabright	Carden Plain	N 44°38'27" W 079°03'59"	alvar shrubland	June - Sept 1997
10	5 km N Almonte	Smith Falls Plain	N 45°16'14" W 076°10'58"	alvar grassland	June - Sept 1997

all alvars sampled, characteristic of particular types of alvars, or whether communities are more affected by the fauna at the regional scale, we identified the species found in dominant numbers at each site. Dominant species were defined as any species comprising more than 5% of carabid specimens collected at that site (Frank and Nentwig 1995). Dominant species were identified for each alvar site and for all sites pooled.

Buddle et al. (2005) provided strong arguments for including rarefaction curves in biodiversity studies. We used EstimateS, version 6.0b1 (Colwell 2001) to generate individual-based rarefied estimates of observed species richness for all sites sampled (except site 9, see comments above). Each curve is the result of 100 randomizations without replacement. Measures of standard deviation were obtained from all randomizations for each site.

Carabidae were identified using Lindroth (1961; 1963; 1966; 1968; 1969a; 1969b). Classification and geographic distribution follow Bousquet and Larochelle (1993). Habitat preferences were based primarily on data in Lindroth (1961; 1963; 1966; 1968; 1969a; 1969b), although other recent information was incorporated when available (Freitag 1999;

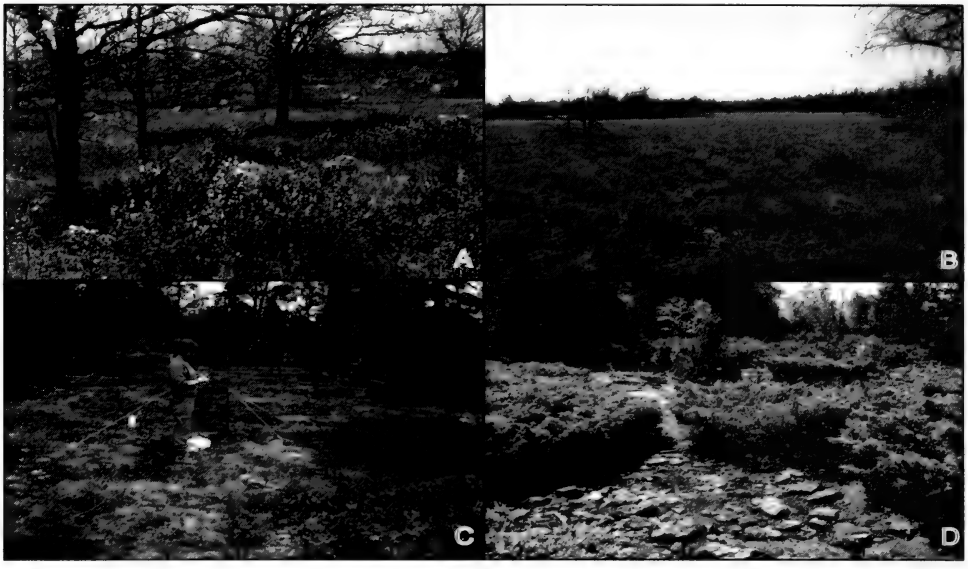

FIGURE 1. Examples of the four alvar types sampled during this study: A) alvar savanna, Manitoulin Island; B) alvar grassland, LaCloche Island; C) alvar pavement, Manitoulin Island; D) alvar shrubland, Manitoulin Island.

Larochelle and Larivière 2003). Species known to occupy four or more of the eight habitat categories were recorded as generalists.

In order to assess the potential interactions of carabid species in different alvar sites, we report on the dispersal ability of each species as determined by the condition of their hind wings. The condition of the hind wings (brachypterous or macropterous) was recorded from Lindroth (1961; 1963; 1966; 1968; 1969a; 1969b) and Larochelle and Larivière (2003). All specimens are deposited in the Lyman Entomological Museum, McGill University, Ste-Anne-de-Bellevue, Quebec, or the Canadian National Collection of Insects, Ottawa, Ontario.

Results

Species richness and abundance

We collected 8647 ground beetles, representing 142 species (Table 2). Excluding site 9, in which most traps were lost during the sampling period, the number of specimens collected per site ranged from 324 (site 8) to 2188 (site 10), and the number of species ranged from 21 (site 2) to 67 (site 5). The four sites with the highest species richness were alvar grasslands (sites 5, 10, 8, 4; Table 2). Sites 5 and 10 had the highest numbers of specimens (1841 and 2188, respectively) and species (67 and 57, respectively). Species richness and numbers of specimens collected were also high in the alvar savanna grassland

TABLE 2. Carabidae collected in Ontario alvars. Hab - habitat (G = generalist, F = forest, M = marsh, Mg = grassy meadow, Mw = wet meadow, Ob = open bare ground, Osw = open wet sand, R = riparian). Site numbers correspond to those in Table 1. Length of the hind wings was recorded as a measure of dispersal ability (+ = macropterous, - = brachypterous, +/- = dimorphic). * = introduced species.

			Alvar site										
Species	**Wings**	**Hab**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**Total**
Acupalpus canadensis Casey	+	M								1			1
Ac. nanellus Casey	±	M					2						2
Ac. partiarius (Say)	+	M				1				1	2		4
Agonum crenistriatum (LeConte)	+	ObMg					13		15			85	113
Ag. cupreum Dejean	±	ObMg			3	35							38
Ag. cupripenne (Say)	+	Ob	4		218	64	202	8	92	32		74	694
Ag. gratiosum (Mannerheim)	+	M							1	1			2
Ag. harrisii LeConte	+	M				3	1			1			5
Ag. lutulentum (LeConte)	+	M					1		1				2
Ag. melanarium Dejean	+	MR			2	2							4
Ag. metallescens (LeConte)	+	M			1								1
Ag. muelleri (Herbst)*	+	Mg			1								1
Ag. nutans (Say)	+	Mg				370	45		2	2		26	445
Ag. placidum (Say)	+	Ob	5			1	1	1	1	1		1	11
Ag. rufipes Dejean	+	Ob					39		22			1	62
Ag. trigeminum Lindroth	+	MR				2	19	1		12		3	37
Amara aeneopolita Casey	+	Mg	1										1
Am. angustata (Say)	+	Mg								1			1
Am. cupreolata Putzeys	±	Mg	7		12	12	8	2	4	1	2	10	58
Am. familiaris (Duftschmid)*	+	Mg					2					1	3
Am. impuncticollis (Say)	+	Mg			1	7	8	10	11	1		5	43
Am. laevipennis Kirby	+	Mg					2			2			4

TABLE 2. Continued

Species	Wings	Hab	Alvar site 1	2	3	4	5	6	7	8	9	10	Total
Am. latior (Kirby)	+	MgOb	2										2
Am. lunicollis Schiødte*	+	Mg								5			5
Am. obesa (Say)	-	Ob	6									11	17
Am. pallipes Kirby	+	Mg				7	2			23			32
Am. pennsylvanica Hayward	+	Mg					57					367	424
Anisodactylus carbonarius (Say)	+	Mg					41					13	54
An. harrisii LeConte	+	MwMg			1			28	8	14		36	87
An. nigerrimus (Dejean)	+	Mg					49	2	13	9		152	225
An. rusticus (Say)	+	Mg					19			2		9	30
An. sanctaecrucis (Fabr.)	+	MRMg					1					1	2
Badister neopulchellus Lindroth	+	M			1	4					1		6
Ba. notatus Haldeman	±	Mg	1			1	1	3	7	5		29	47
Bembidion castor Lindroth	+	MR						1					1
Be. concretum Casey	+	M					1						1
Be. mimus Hayward	+	MR				4	3	39	1	3	1	10	61
Be. mutatum Gemminger & Harold	±	Osw			1					1			2
Be. nitidum (Kirby)	+	Ob			1								1
Be. patruele Dejean	+	MR						3	1			3	7
Be. praticola Lindroth	±	FMw								1			1
Be. rapidum (LeConte)	+	Osw	1				1	12					14
Be. versicolor (LeConte)	+	RM			2	3							5
Brachinus cyanochroaticus Erwin	+	M				2			1			1	4
Br. tenuicollis LeConte	+	M					2						2
Bradycellus lecontei Csiki	+	M				1							1
Bd. neglectus (LeConte)	+	Ob								2		1	3
Bd. nigriceps LeConte	+	M					3	2		1		3	9

TABLE 2. Continued

Species	Wings	Hab	Alvar site 1	2	3	4	5	6	7	8	9	10	Total
Bd. nigrinus (Dejean)	+	MwMg								1			1
Calathus gregarius (Say)	±	ObF	114	47	256	7	1		19	4		6	454
Ca. opaculus LeConte	+	Ob					1					4	5
Calosoma calidum (Fabr.)	+	MgOb	1		7	6	6		1	2		36	59
Carabus maeander Fischer von Waldheim	±	M		1		4	58		17	39		2	121
Cr. nemoralis O.F. Müller*	-	G			9		127					2	138
Cr. serratus Say	±	Ob	36	3	6	2		24	8			5	84
Cr. sylvosus Say	-	F	10							3			13
Chlaenius emarginatus Say	+	F								1	5	1	7
Ch. impunctifrons Say	+	MFR				6							6
Ch. l. lithophilus Say	+	M				1							1
Ch. p. pennsylvanicus Say	+	M				1	1		1	1			4
Ch. p. purpuricollis Randall	+	Ob	13		115	6	8			7		125	274
Ch. s. sericeus (Forster)	+	MRMg			2	1	2	1					6
Ch. t. tomentosus (Say)	+	Ob			1							7	8
Ch. t. tricolor Dejean	+	MgOb	1			3	1						5
Cicindela denikei Brown	+	Ob		14	7								21
Ci. limbalis Klug	+	Ob		3							1	69	73
Ci. l. longilabris Say	+	Ob		9	3								12
Ci. p. purpurea Olivier	+	Ob	2		3					2	7	3	17
Ci. punctulata Olivier	+	Ob									4	2	6
Ci. sexguttata Fabr.	+	FMg					1			1	2		4
Clivina fossor (L.)*	±	Ob				1	5	15	3	2	1	32	59
Cyclotrachelus s. sodalis (LeConte)	-	Mg								12			12
Cymindis americanus Dejean	±	ObMg	1										1

TABLE 2. Continued

Species	Wings	Hab	Alvar site 1	2	3	4	5	6	7	8	9	10	Total
Cm. cribricollis Dejean	±	Ob	1					1					2
Cm. neglectus Haldeman	±	FOb	1		1		4		1		1		8
Cm. pilosus Say	±	Ob					2						2
Dicaelus teter Bonelli	-	F									1		1
Diplocheila obtusa (LeConte)	+	Ob	1		1	1	13	6		3		28	53
Dp. striatopunctata (LeConte)	+	M		1		8							9
Dromius piceus Dejean	+	F	1				1	1			1		4
Dyschirius globulosus (Say)	±	Ob	1		6	1	4	22	6	3	1	15	59
Elaphropus anceps (LeConte)	+	Ob					1	2	1	3		11	18
El. granarius (Dejean)	±	Ob			3		8			2		7	20
El. incurvus (Say)	+	Ob				2			1			2	5
Elaphrus clairvillei Kirby	+	M								1			1
Eu. fuliginosus Say	+	M								1			1
Galerita janus (Fabr.)	+	F					8	1					9
Harpalus affinis (Shrank)*	+	Mg					3	1					4
H. caliginosus (Fabr.)	+	MgOb		1									1
H. compar LeConte	+	Mg	9		4	4							17
H. erythropus Dejean	+	Mg					4			2		109	115
H. faunus Say	+	Mg	1		20	8	486					341	856
H. herbivagus Say	+	MgOb	3				18	1		1		7	30
H. indigens Casey	+	Ob										1	1
H. opacipennis (Haldeman)	+	ObMg	4	1	2			1					8
H. pensylvanicus (DeGeer)	+	Mg	7	1	2		45	4	1	5		45	110
H. plenalis Casey	+	MgOb		2			1	12	1		3		19
H. somnulentus Dejean	+	Mg	21		8	12	20	3	20	11	1	31	127
Lebia atriventris Say	+	Mg								1			1

TABLE 2. Continued

Species	Wings	Hab	Alvar site 1	2	3	4	5	6	7	8	9	10	Total
Le. fuscata Dejean	+	Mg		1			1						2
Le. moesta LeConte	+	Mg					1						1
Le. pumila Dejean	+	Mg		1				11			2		14
Le. viridis Say	+	Mg								1			1
Lophoglossus scrutator (LeConte)	+	M				5							5
Microlestes linearis (LeConte)	±	Ob					1						1
Myas cyanescens Dejean	-	F	3										3
Notiophilus aeneus (Herbst)	+	F			2								2
N. aquaticus (L.)	±	FOb						4					4
N. semistriatus Say	±	Ob	25	2									27
Oodes fluvialis LeConte	+	M							1				1
Ophonus puncticeps Stephens*	+	Mg	4		1	2		2	1				10
Patrobus longicornis (Say)	±	Mw		1			1						2
Platynus decentis (Say)	-	FR						1					1
Poecilus chalcites (Say)	+	MgOb					1	1				1	3
Po. l. lucublandus (Say)	+	MgOb	1	1	309	322	416	1	31	25	1	235	1342
Pterostichus caudicalis (Say)	+	M				2							2
Pt. commutabilis (Motschulsky)	+	Mg			22	26	22	2	17	21		74	184
Pt. coracinus (Newman)	-	F	63	329		1		5	11		1		410
Pt. corvinus (Dejean)	+	M				1	2						3
Pt. femoralis (Kirby)	±	Ob			1	34				22			57
Pt. lachrymosus (Newman)	-	F						2					2
Pt. luctuosus (Dejean)	+	M				23	4		2	1		3	33
Pt. melanarius (Illiger)*	±	G	5	24	43	138	1	3				2	216
Pt. mutus (Say)	+	MgF			1								1
Pt. novus Straneo	-	FObMg	294	33	108	2	22	86	35	16	2	107	705

TABLE 2. Continued

Species	Wings	Hab	Alvar site 1	2	3	4	5	6	7	8	9	10	Total
Pt. patruelis (Dejean)	±	M								3			3
Pt. pensylvanicus LeConte	+	F				1	2		1				4
Pt. tenuis (Casey)	+	M					1		7			1	9
Pt. tristis (Dejean)	-	F		1				1					2
Selenophorus gagatinus Dejean	+	Ob					2			2		24	28
Se. opalinus (LeConte)	+	Ob						1					1
Sphaeroderus c. canadensis Chaudoir	-	F									3		3
Sp. nitidicollis brevoorti LeConte	-	F	1										1
Sp. stenostomus lecontei Dejean	-	F	5			1		3	3			1	13
Stenolophus comma (Fabr.)	+	Ob	3										3
St. conjunctus (Say)	±	Ob			2	2	10			2	2	6	24
St. fuliginosus Dejean	+	M			1	1	2	1				1	6
St. ochropezus (Say)	+	M	2					1					3
Syntomus americanus (Dejean)	±	Ob	1		3	1		2			1		8
Synuchus impunctatus (Say)	±	ObF	39	2	7					1			49
Trechus apicalis Motschulsky	±	F						3					3
T. quadristriatus (Schrank)*	+	Ob	2		1	1		1	3				8
Total species			**41**	**21**	**44**	**52**	**67**	**47**	**39**	**56**	**23**	**57**	**142**
Introduced species			**3**	**1**	**5**	**4**	**5**	**5**	**3**	**2**	**1**	**4**	**9**
Percent introduced species			**7.3**	**4.8**	**11.4**	**7.7**	**7.4**	**10.6**	**7.7**	**3.6**	**4.3**	**7.0**	**6.3**
Total specimens			**703**	**478**	**1201**	**1156**	**1841**	**338**	**372**	**324**	**46**	**2188**	**8647**
Introduced specimens			**11**	**24**	**55**	**142**	**138**	**22**	**7**	**7**	**1**	**37**	**444**
Percent introduced specimens			**1.6**	**5.0**	**4.6**	**12.3**	**7.5**	**6.5**	**1.9**	**2.2**	**2.2**	**1.7**	**5.1**

(site 3), with 44 species and 1201 specimens. Species richness was lowest in the alvar shrubland (site 2, 21 species) although more specimens were collected in that site than in sites 6 (alvar pavement), 7 and 8 (alvar grasslands) (Table 2).

Dominant species

A total of 24 carabid species were collected in dominant numbers. Each site had between four and seven dominant carabid species (Table 3). Only two of the dominant species (*Poecilus l. lucublandus* (Say) and *Pterostichus novus* Straneo) were present at all sites (Table 3). *Poecilus l. lucublandus* was the most frequently collected species overall (1342 specimens, Table 2). *Agonum cupripenne* (Say) was dominant in five sites and present in all except one. *Calathus gregarius* (Say) was dominant in four sites. Of the remaining 20 species, five were dominant in two sites and 15 were dominant only in one. Eight different species ranked first in dominance at the nine sites analyzed (Table 3).

Estimates of species richness

Rarefied estimates of species richness are presented in Figure 2. Overall rarefaction curves (Fig. 2a) show that sampling was incomplete in several sites and additional carabid species remained undetected. Site 10 (alvar grassland, Smith Falls Plain) was the only site for which the accumulation of new species begins to level off (at about 1500-2000 specimens). Six of the sites (1, 3, 4, 5, 7, 10) have overlapping or similar richness based on the subsamples common to all sites (Fig. 2b; N = 300 specimens). These sites include the only alvar savanna sampled, one of the alvar pavements, and most alvar grasslands. Site 2 (alvar shrubland, Manitoulin Island) appears to be significantly less diverse than all other sites while site 8 (alvar grassland, Carden Plain) is the most species rich of all sites (Fig. 2b). The species richness of site 6 (alvar pavement, Bruce Peninsula) is slightly lower than at site 8 but greater than at all other sites.

Introduced species

Nine introduced European species were collected comprising 6.3% of the total species richness: *Agonum muelleri* (Herbst), *Amara familiaris* (Duftschmid), *Am. lunicollis* Schiødte, *Carabus nemoralis* O. F. Müller, *Clivina fossor* (L.), *Harpalus affinis* (Shrank), *Ophonus puncticeps* Stephens, *Pterostichus melanarius* (Illiger), and *Trechus quadristriatus* (Shrank). The number of introduced carabid species collected at each site (Table 2) ranged between one (sites 2 and 9) and five (sites 3, 5, 6). The two sites with the highest proportion of introduced species were sites 6 and 3, representing 10.6% and 11.4% of the species collected at those sites, respectively. Conversely, less than 5% of the carabid species collected on sites 2, 8 and 9 were introduced. Only three species (*Cr. nemoralis, Cl. fossor,* and *Pt. melanarius*) were represented by more than ten specimens (Table 2). There was no consistent pattern in the distribution of introduced species between sites.

For all sites combined, 5.1% of the specimens collected belonged to introduced species. The proportion of introduced species was highest at site 4 (12.3% of all specimens), whereas introduced species comprised less than 2.5% of all specimens at sites 1, 7, 8, 9, and 10 (Table 2).

TABLE 3. Dominant species of Carabidae collected in Ontario alvars. Site numbers correspond to those in Table 1. Dn = rank of dominant species at site (e.g. D1 = most dominant species at site); P - species present but not dominant at site * = introduced species.

	Alvar site									
Species	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**10**	**Total**
Agonum cupripenne	P		D3	D4	D3	P	D1	D2	P	D4
Agonum nutans				D1	P		P	P	P	D6
Agonum rufipes					P		D4		P	
Amara pallipes				P	P			D4		
Amara pennsylvanica					P				D1	
Anisodactylus harrisii			P			D3	P	P	P	
Anisodactylus nigerrimus					P	P	P	P	D4	
Bembidion mimus				P	P	D2	P	P	P	
Calathus gregarius	D2	D2	D2	P	P		D6	P	P	D5
Carabus maeander		P		P	P		P	D1	P	
*Carabus nemoralis**			P		D4				P	
Carabus serratus	D5	P	P	P		D4	P		P	
Chlaenius p. purpuricollis	P		D4	P	P			P	D5	
Dyschirius globulosus	P		P	P	P	D5	P	P	P	
Harpalus erythropus					P			P	D6	
Harpalus faunus	P		P	P	D1				D2	D2
Harpalus somnulentus	P		P	P	P	P	D5	P	P	
Poecilus l. lucublandus	P	P	D1	D2	D2	P	D3	D3	D3	D1
Pterostichus commutabilis			P	P	P	P	P	D6	P	
Pterostichus coracinus	D3	D1		P		P	P			
Pterostichus femoralis			P	P				D5		
*Pterostichus melanarius**	P	D4	P	D3	P	P			P	
Pterostichus novus	D1	D3	D5	P	P	D1	D2	D7	P	D3
Synuchus impunctatus	D4	P	P					P		
Number of dominant species	**5**	**4**	**5**	**4**	**4**	**5**	**6**	**7**	**6**	**6**
Total number of species	**41**	**21**	**44**	**52**	**68**	**47**	**39**	**56**	**57**	**142**

Vagility

Fully developed hind wings are known in at least some specimens of 91% of the species collected (Table 2). Thirteen species are brachypterous (Table 2).

Habitat associations and geographic affinities

A large number of carabids have previously been associated with open, bare ground (50 species, Table 2). A similar number of species occur in grassy meadows (48 species). The third and fourth most common habitats are marshes and forests (37 and 25

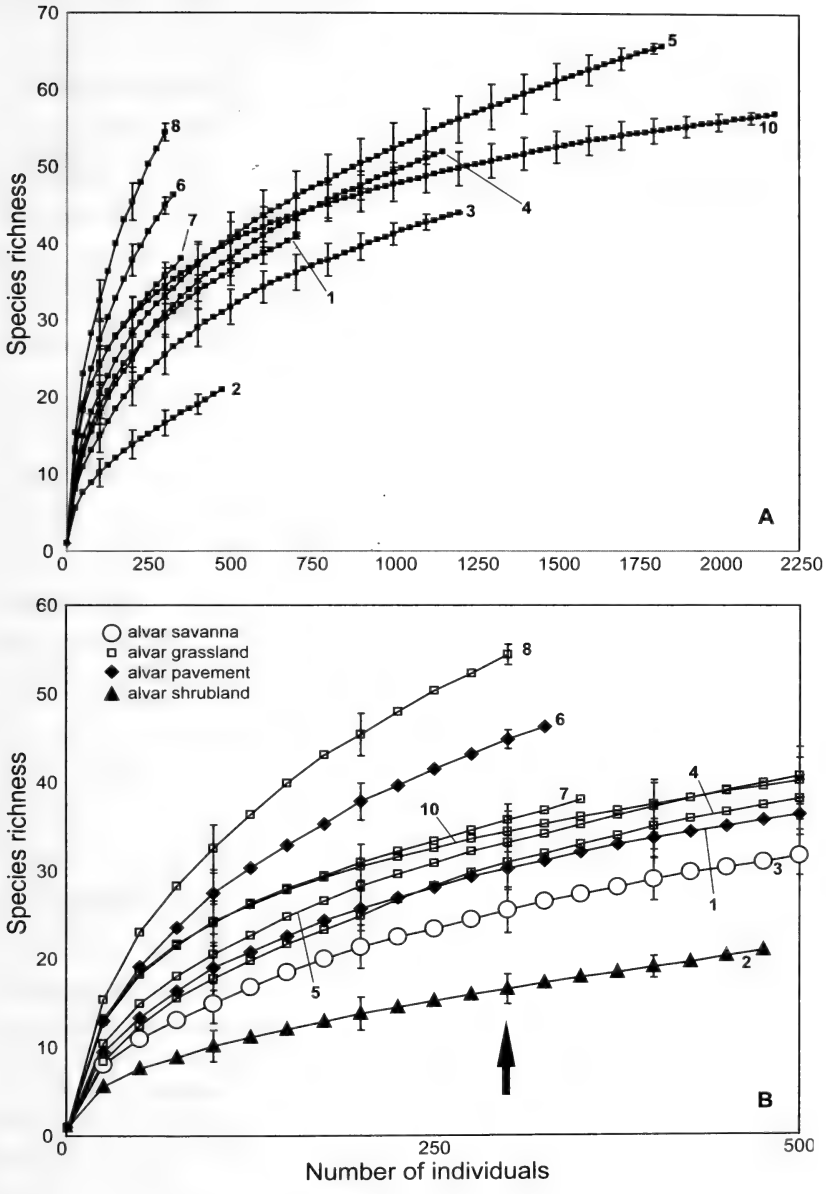

FIGURE 2. Rarefied estimate of species richness for ground beetles (Carabidae) sampled in nine Ontario alvar sites. Data points were plotted for every 25th specimen and measure of variance (± SD) for every 100th specimen. A) rarefaction including all specimens sampled; B) rarefaction based on first 500 specimens (arrow indicates subsample sizes for comparison of species richess). Sites are separated by alvar type.

species, respectively). Less than ten percent of the species occur in either riparian habitats, wet meadows, open wet sand, or are generalists in their habitat requirements.

Most of the species collected are widespread in North America, the rest are restricted to eastern North America. Some species are near the limits of their distribution in the study sites. Species such as *Agonum metallescens* (LeConte), *Amara lunicollis*, *Bradycellus lecontei* Csiki, *Cicindela l. longilabris* Say, and *Lebia moesta* LeConte are boreal species near the southern limit of their ranges. In contrast, species like *Brachinus tenuicollis* LeConte, *Carabus sylvosus, Cyclotrachelus s. sodalis, Cymindis americanus* Dejean, *Dicaelus teter*, *Lophoglossus scrutator* (LeConte), and *Selenophorus opalinus* (LeConte) are southern or southeastern species near the northern limit of their ranges. Most of these species were collected in very low numbers. Of the above-mentioned species only three (*Ci. l. longilabris, Cr. sylvosus*, and *Cy. s. sodalis*) were represented by more than five specimens (Table 2).

All the species collected have previously been recorded in Ontario and few range extensions were noted. *Cicindela denikei* Brown was previously known only from a small area near the borders of Ontario, Manitoba, and Minnesota (Kaulbars and Freitag 1993; Freitag 1999). Manitoulin Island represents a significant southeastern extension of the known range and the species appears to be abundant in appropriate alvar sites on the island. We did not collect *Ci. denikei* in alvars on the mainland.

All of the introduced species are widespread in North America except *Ophonus puncticeps,* which is at the western edge of its North American range in Ontario, and *Trechus quadristriatus*, which is known in North America only from Quebec, Ontario, Michigan, and Wisconsin (Bousquet and Larochelle 1993).

Discussion

Species richness and abundance

The total number of carabid species recorded in each alvar site sampled ranged from 21 to 67. The lowest species richness occurred in the alvar shrubland of Manitoulin Island (site 2, Table 2). Approximately 65% of this site is covered with shrubs such as common juniper (*Juniper communis* L. Cupressaceae) whereas the rest is composed almost entirely of large blocks of limestone separated by narrow and deep cracks. This type of habitat can be compared to similar alvars with poor vegetation diversity in Sweden (Sylvén 1983). In Europe, this alvar type, although not as rich in carabid species as sites that are more diverse botanically, is thought to support a unique insect fauna and should not be discarded from a conservation point of view based on low species number (Coulianos and Sylvén 1983).

Carabid species richness was consistently higher in alvar grasslands, with most sites supporting more than 50 species each (Table 2). These results are comparable to those reported for European alvars (Coulianos and Sylvén 1983) where the highest number of arthropod species was recorded in sites with rich vegetation. Alvar pavement and alvar savanna sites were also species-rich with between 40 and 50 carabid species each.

Recent investigations of carabid diversity in different types of open habitats in northeastern North America have reported between 26 and 76 carabid species from a single

site (Table 4). Additionally, Canadian agroecosystems typically support between 40 and 60 carabid species at a single site (Goulet 2003). The two alvar shrublands sampled during our study fall below the carabid species richness values recorded in other open habitats. On the other hand, alvar grasslands occupy the higher end of the scale of carabid species richness with more than 50 species. The alvar pavements as well as the alvar savanna support carabid species richness similar to that of typical agroecosystems.

Generally speaking, the more species-rich sites (grasslands, savanna, and pavements) support larger populations of ground beetles based on our trap catches. More than 1000 specimens were collected on sites 3, 4, and 5, and more than 2000 specimens at site 10 (Table 2). However, carabid abundance was not closely correlated with species richness in all sites. For example, the species-rich alvars at Miller Lake (site 6) and Dalrymple (site 8) supported comparatively very low numbers of specimens (less than 400 each).

Dominant species

Species such as *Poecilus l. lucublandus* and *Pterostichus novus* were dominant in several sites and present in all alvars sampled. Whereas *Po. l. lucublandus* is a species commonly encountered in grassy meadows throughout its range (Lindroth 1966; Tyler and Ellis 1979; Levesque and Levesque 1987, 1994; Boivin and Hance 1994; Byers et al. 2000), the presence of *Pt. novus* in Ontario alvars in such numbers was not expected. The latter species has been collected in high numbers in different types of forests outside of Ontario (e.g. Snider and Snider 1986; Epstein and Kulman 1990). The numerous captures of this species in southern Ontario alvars (> 700 specimens) indicate that this species is closely associated with this type of habitat (Bouchard et al. 1998). Three species (*Agonum cupripenne*, *Dyschirius globulosus*, and *Harpalus somnulentus*) were recorded in dominant numbers in some alvars and were present in all sites except for the alvar shrubland on Manitoulin Island (Table 3). As mentioned above, the alvar shrublands support the lowest carabid beetle species richness of all alvars sampled. The harsh microclimatic conditions in alvar shrublands seem to be an important factor in excluding certain species found commonly in all other sites sampled.

Five dominant species were collected only in alvar grasslands: *Agonum nutans*, *Ag. rufipes*, *Amara pallipes*, *Am. pennsylvanica*, and *Harpalus erythropus*. Of these, *Ag. nutans* was the most numerous carabid in the alvar grassland of Manitoulin Island and was the only species present in all other alvar grasslands. Although widespread in North America, most of the specimens of *Ag. nutans* recorded in Canada prior to this study were from the shore of Lake Erie (Lindroth 1966). Based on the uncommon catches of this species outside of alvars in Ontario, it now appears that *Ag. nutans* is very closely associated with alvar grasslands in the province (Bouchard et al. 1998). The presence of *Carabus serratus* in dominant numbers only in alvar pavements is also noteworthy. This species, although collected in small numbers in other alvar types, seems to prefer sites with moss or lichen-covered, flat limestone with sparse grasses and shrubs growing in cracks.

Some species of dominant ground beetles were either only recorded in or only dominant in the two alvars of eastern Ontario (*Amara pennsylvanica* and *Harpalus faunus*). Other species such as *Pterostichus coracinus* and *Pt. melanarius* were collected in dominant numbers only in alvars of Manitoulin Island. These observations indicate that the ground beetle community of Ontario alvars can also be influenced by regional assemblages.

TABLE 4. Recent studies on carabid fauna in open habitats in northeastern North America. a = old plants; b = young plants; NY = New York; PA = Pennsylvania; QC = Quebec; VM = Vermont. All studies used pitfall traps to collect the carabid fauna.

	Levesque & Levesque (1987)	Boivin & Hance (1994)	Levesque & Levesque (1994)	Levesque & Levesque (1994)	Byers et al. (2000)	Byers et al. (2000)	Byers et al. (2000)
Habitat	Meadow	Carrot field & field edges	Raspberry[a] plantation	Raspberry[b] plantation	Pasture	Pasture	Pasture
Province or state	QC	QC	QC	QC	PA	NY	VM
Number localities sampled	1	1	1	1	5	3	3
Total species	26	76	45	32	85	40	54
Introduced species	4	5	10	7	6	10	13
Percent introduced species	15.4	6.6	22.2	21.9	7.1	25.0	24.1
Total specimens	1127	7700	5375	3806	4365	618	1366
Introduced specimens	113	2266	4493	3085	2653	334	792
Percent introduced specimens	10.0	29.4	83.6	81.1	60.8	54.0	58.0

Estimates of species richness

The majority of alvar sites sampled in this study have overlapping or similar rarefaction curves when estimates are standardized to sampling effort (Fig. 2b). The two major exceptions to this trend are sites 2 and 8. Site 2 (the only alvar shrubland included in the analysis) is significantly less diverse than all other sites. This result is consistent with studies on Swedish alvars (Coulianos and Sylvén 1983) and is thought to reflect the lower microhabitat diversity available to ground beetles in alvar shrublands. Site 8 (alvar grassland, Carden Plain) is the most species-rich alvar sampled. The high number of singletons (N=22) and doubletons (N=11) in this site, combined with the low number of specimens (N=324) result in a rarefaction curve that show no signs of leveling off (Fig. 2a).

Introduced species

Of the approximately 470 species of ground beetles that occur in eastern Canada, 41 (8.7%) are introduced European species that have become established predominantly in disturbed ecosystems. Although the number of introduced carabid species in disturbed sites may represent a small proportion of the overall species richness (when compared to native species), these species can often dominate trap catches (Goulet 2003).

The number of introduced ground beetle species in the sampled Ontario alvars ranged between one, in the alvar shrubland sites, and five, in sites on Manitoulin Island, the Napanee Plain and the Bruce Peninsula, respectively (Table 2). The number of introduced species recorded in other recent studies on the carabid fauna of various open habitats in eastern North America ranged between 4 and 13 (Table 4). The alvar shrublands in Ontario, as for similar alvars in Sweden (Coulianos and Sylvén 1983), can be considered relatively undisturbed by human activity. This hypothesis is supported the current study by the very low number of introduced species that have invaded these harsh habitats. The alvar sites with four or five introduced species are usually sites with rich vegetation that have been used in the past as pastures for farm animals (e.g. alvar savanna and alvar grassland on Manitoulin Island).

Ground beetle communities, such as those recorded by Levesque and Levesque (1994) in raspberry plantations, can be composed of more than 80% introduced species in some sites. The overall percentage of introduced specimens in the Ontario alvars was low in most sites with values below 5% (Table 2). The site with the greater percentage of introduced specimens was the alvar grassland of Manitoulin Island (12.3%), a site that has been used in the past for grazing. Even with a value of more than 12%, the alvar grassland of Manitoulin Island supports what can be considered a relatively undisturbed ground beetle community when compared to those reported in other studies (Table 4).

Vagility

The majority of ground beetles collected in Ontario alvars have the ability to fly at some stage during their life cycle. Of the thirteen brachypterous species recorded during our study, only three occur in dominant numbers in at least one site (*Carabus nemoralis*, *Pterostichus coracinus*, and *Pt. novus*). *Carabus nemoralis* is an introduced species that has a large population in the alvar grassland of the Napanee Plain. *Pterostichus coracinus*

occurs in large numbers on the alvar pavement and alvar shrubland on Manitoulin Island. Because alvar pavement sites on Manitoulin Island are now preserved, and because this species has close associations with forested areas neighboring alvar sites, its survival on the island seems secure. *Pterostichus novus*, however, is closely associated with alvars in southern Ontario (Bouchard et al. 1998) and the reduced dispersal ability of this species could pose a threat to local populations in certain areas.

Habitat associations and geographic affinities

Given the nature of alvars, it is reasonable to predict that the carabid fauna would be dominated by species associated with open dry habitats. Because of the occurrence of spring flooding and the frequent persistence of temporary pools in many of the sites, hygrophilous species would be expected to comprise another important component of the fauna. Forest species and those associated with riparian habitats would be expected in lower numbers, usually as a result of movement from adjacent suitable habitats that border or surround many of the alvar sites.

These predictions were largely confirmed by our results (Table 2). More than thirty percent of all species are known to occur in open bare ground or grassy meadows throughout their North American range (e.g. *Amara* spp.). Nineteen of the twenty-four dominant species in Table 3 (79.2%) typically occur in dry open habitats or grassy meadows. The presence of seasonal flooding has a major influence on the ground beetle communities of most alvars, with 26% of all species recorded being associated with marsh habitats (e.g. some *Agonum* spp.). Populations of *Ag. nutans*, a species rarely collected in Ontario which seems closely associated with alvar grasslands, are thought to increase with the presence of small bodies of water in those habitats (Bouchard et al. 1998). *Bembidion mimus* and *Carabus meander* are typically associated with wet habitats throughout their ranges and are found in dominant numbers in one Ontario alvar site each (Table 3). Forest ground beetles make up a lesser component of the alvar fauna (18% of all species). Most of the forest species were collected in small numbers except for *Pterostichus coracinus* which was found in dominant numbers at two sites on Manitoulin Island. Both sites are surrounded by forests. Ground beetles known to occur in riparian habitats, open wet sand, and wet meadows make up only a small percentage of the Ontario alvar communities.

The Carabidae, dominated by widespread and eastern Nearctic species, do not show the same geographic pattern as the plants. The flora of Ontario alvars consists of a combination of southern, northern, and western species, along with some endemic species (Catling and Brownell 1995). The presence of boreal and western plant species probably resulted from range expansion of this flora in periglacial communities along the front of the continental ice sheet. Following glacial retreat, relict populations remained in suitable open habitats such as alvars. The southern flora probably colonized alvars later, during the expansion of prairie communities in the Hypsithermal (Catling and Brownell 1995). The presence of western carabid species such as *Chlaenius p. purpuricollis* in Great Lakes alvars probably results from the existence of more continuous prairie habitat during the Hypsithermal. This pattern is also seen in the distribution of several species of leafhoppers (Homoptera: Cicadellidae) (Bouchard et al. 2001).

Most ground beetles are generalized predators, and their patterns of distribution and habitat association are generally associated with climatic and physical features of the

habitat rather than the distribution of prey species or plant communities (Campbell et al. 1979). As a result, close correspondence between geographic or habitat affinities of carabids and plants was not expected in this study. Nevertheless, a small number of species showed notable patterns of distribution.

Agonum nutans, *Chlaenius p. purpuricollis*, and *Pterostichus novus* were all dominant in this study and have rarely been collected in Ontario except in alvars. Because of this, Bouchard et al. (1998) considered them alvar-associated species in the region. However, all three have been collected in other habitats outside of Ontario.

Agonum nutans was present in all the alvar grasslands, but was dominant in only one. It was not collected in other alvar types. Based on the few published records of this species, Bouchard et al. (1998) considered *Ag. nutans* associated with open grassy areas in the Great Lakes region.

Pterostichus novus was collected at all alvar sites, and was one of the most dominant species. Although it is apparently associated with alvars in Ontario (Bouchard et al. 1998), many specimens have been collected in a range of habitats including upland and mesic deciduous forests and mesic old fields in Michigan and Minnesota (Snider and Snider 1986; Epstein and Kulman 1990). Because of variation in habitat use, phenology, and morphological characters throughout its range, Bouchard et al. (1998) suggested that *Pt. novus* may represent a complex of species.

Chlaenius purpuricollis purpuricollis was collected in six of the sites and was dominant in two. The main range of *Ch. p. purpuricollis* extends over the prairie ecotone and they are found in well drained, open grasslands. In Ontario it has been recorded only from alvars.

Cicindela denikei has a restricted range in northwestern Ontario, southeastern Manitoba, and northeastern Minnesota and is associated with dry open substrates, usually near forest stands (Kaulbars and Freitag 1993). The Manitoulin Island population is apparently disjunct from the western population and given its apparent habitat preferences, *Ci. denikei* may be restricted to alvars in Ontario.

The major obstacle to characterizing the carabid community of the Great Lakes alvars is the lack of similar studies on native, open habitats other than alvars in the region. If the dominant species identified in this study are also dominant elsewhere in the region, it may be in habitats such as savannas, tallgrass prairie outliers, or sand beach and dune ecosystems. Comprehensive inventories of Carabidae using standardized sampling programs should be undertaken in more of those habitats in order to establish the distribution, abundance, and habitat preferences of "alvar" carabids in the Great Lakes region.

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References

Boivin, G. and T. Hance. 1994. Phenology and distribution of carabid beetles (Coleoptera: Carabidae) in muck-grown carrots in southwestern Quebec. pp. 417-424, *In* Carabid beetles: ecology and evolution. Desender, K., M. Dufrêne, M. Loreau, M. L. Luft, and J. P. Maelfait (eds). Kluwer Academic Publishers. Dordrecht.

Bouchard, P., H. Goulet, and T. A. Wheeler. 1998. Phenology and habitat preferences of three species of ground beetles (Coleoptera: Carabidae) associated with alvar habitats in southern Ontario. Proceedings of the Entomological Society of Ontario 129: 19-29.

Bouchard, P., K. G. A. Hamilton, and T. A. Wheeler. 2001. Diversity and conservation status of prairie endemic Auchenorrhyncha (Homoptera) in alvars of the Great Lakes region. Proceedings of the Entomological Society of Ontario 132: 39-56.

Bousquet, Y. and A. Larochelle. 1993. Catalogue of the Geadephaga (Coleoptera: Trachypachidae, Rhysodidae, Carabidae including Cicindelini) of America north of Mexico. Memoirs of the Entomological Society of Canada 167: 1-397.

Buddle, C. M., J. Beguin, E. Bolduc, A. Mercado, T. E. Sackett, R. D. Selby, H. Varady-Szabo, and R. M. Zeran. 2005. The importance and use of taxon sampling curves for comparative biodiversity research with forest arthropod assemblages. Canadian Entomologist 137: 120-127.

Byers, R. A., G. M. Barker, R. L. Davidson, E. R. Hoebeke, and M. A. Sanderson. 2000. Richness and abundance of Carabidae and Staphylinidae (Coleoptera), in northeastern dairy pastures under intensive grazing. Great Lakes Entomologist 33: 81-105.

Campbell, J. M., G. E. Ball, E. C. Becker, D. E. Bright, J. Helava, H. F. Howden, R. H. Parry, S. B. Peck, and A. Smetana. 1979. 40. Coleoptera. pp. 357-363. *In* Canada and its insect fauna. H. V. Danks (ed). Memoirs of the Entomological Society of Canada. No. 108.

Catling, P. M. and V. R. Brownell. 1995. A review of the alvars of the Great Lakes region: distribution, composition, biogeography and protection. Canadian Field-Naturalist 109: 143-171.

Colwell, R. K. 2001. *EstimateS*: statistical estimation of species richness and shared species from samples. Version 6.0bl. Computer software, user's guide and application. http://viceroy.eeb.uconn.edu/estimates.

Coulianos, C. C. and E. Sylvén. 1983. The distinctive character of the Great Alvar (Öland, Sweden) from an entomological point of view. Entomologisk Tidskrift 104: 213-234.

Epstein, M. E. and H. M. Kulman. 1990. Habitat distribution and seasonal occurrence of carabid beetles in east-central Minnesota. The American Midland Naturalist 123:

209-225.

Frank, T. and W. Nentwig. 1995. Ground dwelling spiders (Araneae) in sown weed strips and adjacent fields. Acta Oecologica 16:179-193.

Freitag, R. 1999. Catalogue of the tiger beetles of Canada and the United States. NRC Research Press, Ottawa. 195pp.

Goulet, H. 2003. Biodiversity of ground beetles (Coleoptera: Carabidae) in Canadian agricultural soils. Canadian Journal of Soil Science 83: 259-264.

Kaulbars, M. M. and R. Freitag. 1993. Geographical variation, classification, reconstructed phylogeny, and geographical history of the *Cicindela sexguttata* group (Coleoptera: Cicindelidae). The Canadian Entomologist 125: 267-316.

Larochelle, A. and M. C. Larivière. 2003. A natural history of the ground-beetles (Coleoptera: Carabidae) of America north of Mexico. Pensoft. Sofia. 583pp.

Levesque, C. and G. Y. Levesque. 1987. Activité, succession saisonnière et taille de coléoptères épigés d'un pré du sud du Québec. Naturaliste Canadien 114: 495-506.

Levesque, C. and G. Y. Levesque. 1994. Abundance and seasonal activity of ground beetles (Coleoptera: Carabidae) in a raspberry plantation and adjacent sites in southern Québec (Canada). Journal of the Kansas Entomological Society 67: 73-101.

Lindroth, C. H. 1961. The ground-beetles (Carabidae, excl. Cicindelinae) of Canada and Alaska. Part 2. Opuscula Entomologica Supplementum 20: 1-200.

Lindroth, C. H. 1963. The ground-beetles (Carabidae, excl. Cicindelinae) of Canada and Alaska. Part 3. Opuscula Entomologica Supplementum 24: 201-408.

Lindroth, C. H. 1966. The ground-beetles (Carabidae, excl. Cicindelinae) of Canada and Alaska. Part 4. Opuscula Entomologica Supplementum 29: 409-648.

Lindroth, C. H. 1968. The ground-beetles (Carabidae, excl. Cicindelinae) of Canada and Alaska. Part 5. Opuscula Entomologica Supplementum 33: 649-944.

Lindroth, C. H. 1969a. The ground-beetles (Carabidae, excl. Cicindelinae) of Canada and Alaska. Part 6. Opuscula Entomologica Supplementum 34: 945-1192.

Lindroth, C. H. 1969b. The ground-beetles (Carabidae, excl. Cicindelinae) of Canada and Alaska. Part 1. Opuscula Entomologica Supplementum 35: I-XLVIII.

Lundberg, S. 1983. Beetles (Coleoptera) on the Great Alvar of Öland. Entomologisk Tidskrift 104: 121-126.

Reschke, C., R. Reid, J. Jones, T. Feeney, and H. Potter. 1999. Conserving Great Lakes alvars. Final Technical Report of the International Alvar Conservation Initiative. The Nature Conservancy, Chicago. 241pp.

Snider, R. M. and R. J. Snider. 1986. Evaluation of pit-trap transects with varied trap spacing in a northern Michigan forest. The Great Lakes Entomologist 19: 51-61.

Sylvén, E. 1983. Studies on the insect and spider fauna of the Great Alvar on the island of Öland, Southern Sweden – background, goal and arrangement. Entomologisk Tidskrift 104: 90-95.

Tyler, B. M. J. and C. R. Ellis. 1979. Ground beetles in three tillage plots in Ontario and observations on their importance as predators of the Northern Corn Rootworm, *Diabrotica longicornis* (Coleoptera: Chrysomelidae). Proceedings of the Entomological Society of Ontario 110: 65-73.

INFLUENCE OF COLOUR AND TRAP HEIGHT ON CAPTURES OF ADULT PEA LEAFMINER, *LIRIOMYZA HUIDOBRENSIS* (BLANCHARD) (DIPTERA: AGROMYZIDAE), IN CELERY

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Abstract

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Sticky trap colour preference and spatial distribution of adult pea leafminer in celery were evaluated in 2001 and 2002 for use in developing an integrated approach to managing this pest. Colour preference was determined by exposing traps of various colours (red, blue, violet, green, white, and yellow) and materials (cardboard and acetate) to leafminer populations in celery for 24-48 hours. To evaluate the vertical distribution of flying adults, yellow sticky cards were positioned at standard heights (10, 30, 50, 70, and 90 cm) within celery crops of varying height for 24-48 hours. All cards were returned to the lab where sex and total number of adult pea leafminer were determined. Both sexes of adult pea leafminer were preferentially attracted to yellow opaque or translucent sticky cards, with highest captures occurring about 20 cm below the crop the top of the celery crop canopy.

Introduction

The pea leafminer, *Liriomyza huidobrensis* (Blanchard), was initially identified in the Holland Marsh region of Ontario in 1999 after causing significant economic loss in leafy vegetable crops (McDonald et al. 2000). This polyphagous pest is established in the sub-tropical and temperate regions of North and South America, Europe, and Asia (Spencer 1973; Weintraub and Horowitz 1995). Since its discovery in Ontario, the pea leafminer has remained geographically isolated within the Holland Marsh region, where it appears to survive the winter within greenhouses (Martin et al. 2005). Local crops experiencing damage include lettuce (*Lactuca sativa* Linnaeus), spinach (*Spinacia oleracea* Linnaeus), celery (*Apium graveolens* Linnaeus), Asian crucifers (*Brassica* spp.), greenhouse ornamentals, greenhouse cucumbers (*Cucumis sativus* (Linnaeus)), and onions (*Allium cepa* Linnaeus).

Insect monitoring is an important management practice required to track pest presence within a field effectively and time control measures accurately. Sampling methods used for monitoring leafminers include adult counts on sticky traps, pupal collections, counts

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of mines, and live larval counts within leaves (Levins et al. 1975; Poe et al. 1978; Johnson et al. 1980). Not all of these techniques are reliable or efficient, as large errors in estimation may occur, counts of adult and pupal stages are not representative of larval populations, and a detrimental time delay in implementing control measures may occur by attempts to forecast future populations (Zehnder and Trumble 1984; Heinz and Chaney 1995). In the Holland Marsh, pea leafminer monitoring in celery, *Apium graveolens* Linnaeus, occurs indirectly from systems in place for established pests or by visual damage assessments. Although sticky card captures may not provide enough information to accurately time pest control programs, this is the simplest and most efficient monitoring method used in the area and it provides growers with information about levels of adult infestation in their crops. The potential for severe economic losses make early detection and continued monitoring of this pest particularly important. The purpose of this research was to determine the most effective colour and placement of sticky traps within the celery canopy to maximize adult pea leafminer captures.

Materials and Methods

All experiments were conducted in plots of celery cv. Florida 683 grown on muck soil (60% organic matter) at the University of Guelph Muck Crops Research Station, Kettleby, ON.

Trap Colour. Card stock (white poster board, Hilroy, Toronto, ON) was painted with two to three coats of exterior or interior acrylic latex paint (The General Paint Store, Cambridge, ON), and cut into 28 x 10 cm cards. Cards were folded in half (14 x 10 cm) with the painted surface exposed. Just prior to placement in the field, traps were coated with medium grade Sticky Stuff® (Olson Products, Medina, OH). Commercial, translucent yellow sticky traps (Cooper Mill Ltd., Madoc, ON) were also included as a standard (14 x 10 cm). All traps were fastened to wooden stakes using bullclips and were oriented facing north/south between the two centre rows of a four row celery bed.

In 2001, six colours (paint formulations provided in parentheses) were evaluated: white (71-011: A1/2, T1/2), violet (81-054: E44, L2, V1Y40), blue (71-052: AC079N), green (71-054: A2Y, T1, Kx6), yellow (71-054: A2Y10, T1, Kx8), and red (15-101). Traps were placed at the top of the canopy (approximately 62 cm). All treatments were replicated six times on three consecutive days (28-30 August) in a completely randomized design. After each 24 hour exposure period, cards were collected and the sex and number of all pea leafminers on the total trap surface were determined using a dissecting microscope (25x).

In 2002, the heights of 30 randomly selected celery plants were measured and the average crop height was determined prior to each experimental period. All traps were placed at half of the average crop height for that experimental period, and were arranged in a completely randomized design with five replications per exposure period. In order to examine the effect of light transmission through traps on pea leafminer captures, paints were applied to both card stock and plastic (overhead transparency film, Basics Office Products, Kitchener, ON) cards to create opaque and translucent traps, respectively. Due to low captures on red, blue, and violet traps in 2001, only white, green, and yellow were included. Traps were established in the field on 6 and 20 August, 5 September, and 2 October 2002

for 48 hours after which they were returned to the lab where sex and total number of adult pea leafminer were determined.

Spectral reflectance curves of all trap colours and types were determined by spectrophotometer (DataFlash 100 spectrophotometer, Datacolour, Lawrenceville, NJ) and are presented in Figure 1. For translucent and commercial yellow traps, reflectance values were determined for traps placed against both white and black backgrounds; spectral reflectance curves were created using the mean percent reflectance values from both

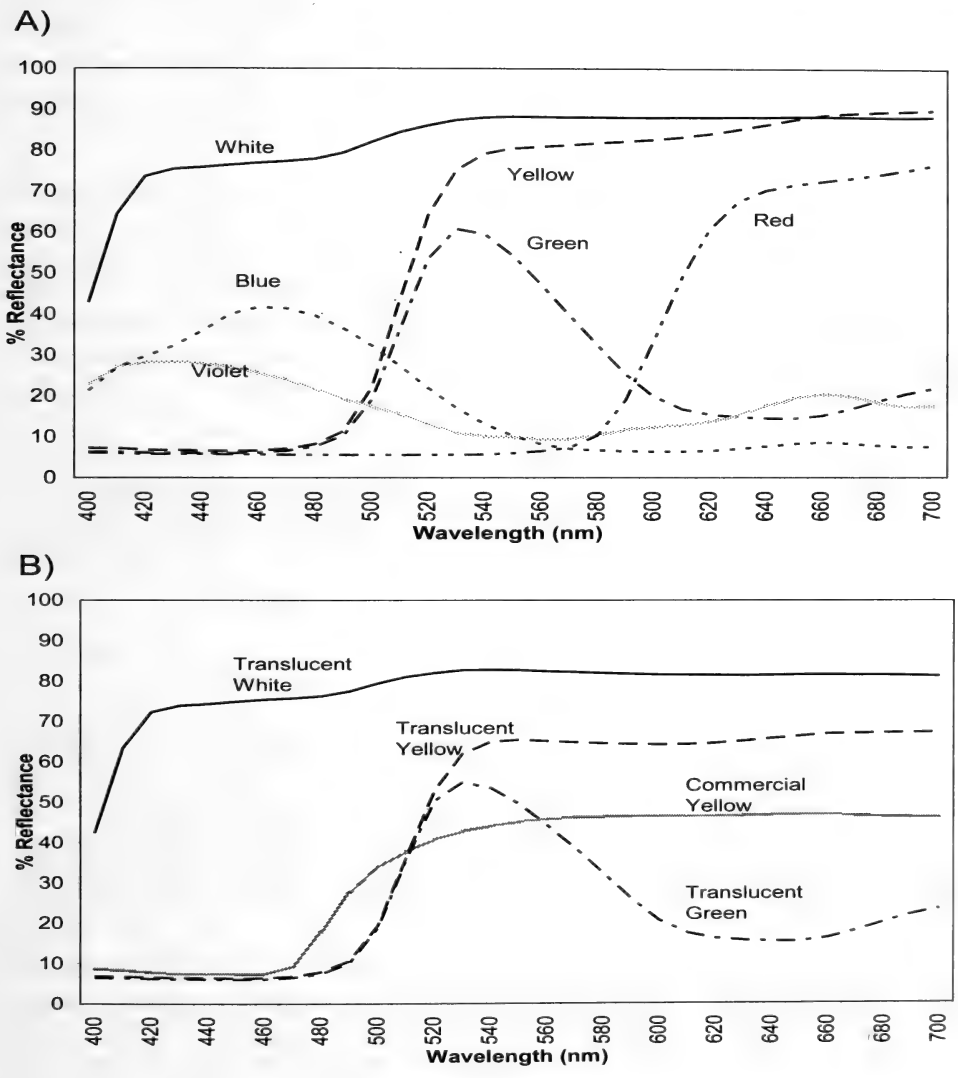

FIGURE 1. Spectral reflectance curves of A) opaque trap colors and B) translucent trap colors, determined by DataFlash 100 spectrophotometer.

backgrounds (Figure 1B).

Trap height. In 2001, yellow commercial sticky traps measuring 14 x 10 cm were fastened individually to wooden stakes using bullclips at heights of 10, 30, 50, 70, or 90 cm from the soil to the bottom of the trap and positioned between the two centre rows of a four row celery bed. Sticky cards were arranged in a completely randomized design with nine replications per day for two days. On 3 and 6 September 2001, traps were exposed for 24 hours, after which the sex and total number of pea leafminer adults on each trap were determined. Average crop height was approximately 65 cm throughout this experiment.

In 2002, yellow commercial individual sticky cards were fastened to wooden stakes at 10, 30, 50, 70, and 90 cm above the soil, using a completely randomized design with eight replications. Traps were positioned between the two centre rows of a four row celery bed on 1 and 14 August, and 17 September 2002, when mean crop heights were 30, 50 and 70 cm, respectively. Traps were exposed for 48 hours after which sex and total number of pea leafminer adults on each trap were determined.

Statistical analyses. Colour data from both years and height data from 2001 were analyzed by analysis of variance (ANOVA) using PROC GLM (SAS Institute, 1999) after transformation by log (x + 0.5). In 2002, numerical heights were renamed according to their relative placement within the canopy (i.e., 60 cm below, 40 cm below, 20 cm below, at, 20 cm above, 40 cm above, and 60 cm above the crop canopy); data for all exposure periods were pooled and analysed as described above. Since trap placement was based on crop height at the time of trap exposure not all relative trap positions could be tested at each exposure period (i.e. 60 cm below the canopy was not applicable when crop height was 50 cm). Two basic assumptions of ANOVA, i.e. 1) independent treatment and model effects and 2) random, independent, and normally distributed errors, were verified prior to analysis. Height and colour were ranked in order of attractiveness by males, females, and total using Tukey's Honestly Significant Difference test. In all cases, $\alpha = 0.05$ and actual, rather than transformed, data are presented.

Results

Trap colour. In 2001, the commercial yellow sticky card captured the most female ($F = 85.26$; df = 6, 109; $P<0.0001$) and male ($F = 87.06$; df = 6, 109; $P<0.0001$) pea leafminers, followed by painted yellow and green sticky cards (Table 1). More males were captured on white than violet sticky cards, but there were no significant differences in captures of females on white, blue, red, and violet sticky cards. Significant date ($F = 5.55$; df = 2, 109; $P = 0.0051$) and replicate ($F = 4.80$; df = 5, 109; $P = 0.0005$) effects were observed.

In 2002, significantly more males ($F = 10.53$; df = 6, 107; $P<0.0001$) and females ($F = 18.60$; df = 6, 125; $P<0.0001$) were captured on yellow sticky cards than on all other trap types (Table 2). For females, commercial and translucent yellow sticky cards were significantly more attractive than opaque yellow cards, but for males there was no difference between the three types of yellow cards. Translucent green and white traps did not capture more pea leafminer than their opaque counterparts. There were significant date*treatment interactions for males ($F = 2.69$; df = 18, 107; $P = 0.0009$) and total pea leafminer captured

TABLE 1. Effect of trap color on the number of male, female, and total adult pea leafminer, *Liriomyza huidobrensis*, captured on sticky traps in three 24-hour trapping sessions between 28 and 30 August 2001. Data for all trapping sessions were combined.

	Mean (± SE) Number of Pea Leafminer Adults Captured[1]		
Trap Colour	**Male**	**Female**	**Total**
Commerical Yellow	138.73 ± 14.85 **a**	48.73 ± 4.48 **a**	187.47 ± 16.19 **a**
Yellow	32.83 ± 7.60 **b**	15.39 ± 3.58 **b**	48.22 ± 11.02 **b**
Green	19.56 ± 2.41 **b**	8.33 ± 0.90 **b**	27.89 ± 3.15 **b**
White	5.50 ± 1.02 **c**	3.22 ± 0.67 **c**	8.22 ± 1.82 **c**
Blue	5.00 ± 1.25 **cd**	2.56 ± 0.37 **c**	7.72 ± 1.43 **c**
Red	2.78 ± 0.45 **cd**	2.22 ± 0.36 **c**	5.33 ± 0.62 **c**
Violet	1.94 ± 0.38 **d**	1.94 ± 0.76 **c**	3.89 ± 1.06 **cd**

[1]Means in the same column followed by the same letter are not significantly different, ANOVA and Tukey's HSD comparisons of means, $\alpha = 0.05$.

TABLE 2. Effect of trap color and translucence on the number of male, female, and total adult pea leafminer, *Liriomyza huidobrensis*, captured on sticky traps in 2002. Data for all dates were combined.

	Mean (± SE) Number of Pea Leafminer Adults Captured[1]		
Trap Colour	**Male**	**Female**	**Total**
Commercial Yellow	14.95 ± 5.20 **a**	40.40 ± 14.46 **a**	55.35 ± 19.21 **a**
Translucent Yellow	10.90 ± 3.52 **ab**	34.00 ± 11.68 **a**	44.90 ± 14.84 **a**
Opaque Yellow	9.10 ± 2.76 **ab**	17.00 ± 5.71 **b**	26.20 ± 8.24 **b**
Translucent Green	6.95 ± 2.94 **bc**	12.20 ± 4.57 **bc**	19.15 ± 7.38 **bc**
Opaque Green	4.05 ± 1.23 **bcd**	6.85 ± 1.91 **bc**	10.90 ± 2.89 **bc**
Translucent White	2.74 ± 1.52 **d**	10.00 ± 3.76 **bc**	12.74 ± 5.10 **cd**
Opaque White	1.85 ± 0.61 **cd**	4.55 ± 1.36 **c**	6.40 ± 1.79 **d**

[1]Means in the same column followed by the same letter are not significantly different, ANOVA and Tukey's HSD comparisons of means, $\alpha = 0.05$.

($F = 2.02$; df = 18, 107; $P = 0.0142$). These interactions were apparently due to low insect captures on 6 and 20 August, which led to a lack of significant model effects on 6 August for males. As patterns of capture on the remaining dates (5 September and 1 October) were almost identical to those for all dates combined, all data were pooled (Table 2).

Trap height. In 2001, captures of both males (3 September: $F = 65.90$; df = 4, 32; $P<0.0001$, 6 September: $F = 54.01$; df = 4, 32; $P<0.0001$) and females (3 September $F = 121.62$; df = 4, 32; $P<0.0001$, 6 September: $F = 135.49$; df = 4, 32; $P<0.0001$) were significantly higher on traps placed at either 30 cm or 50 cm height than at other heights, with more males than females being captured at 30 cm on 3 September (Table 3). Male and female captures at 10 cm trap height were low to intermediate and captures decreased with increasing trap heights above 50 cm. A significant date*treatment interaction for both males ($F = 10.56$; df = 4, 72; $P<0.0001$) and females ($F = 7.00$; df = 4, 72; $P<0.0001$) captured prevented the pooling of data from both experimental periods. On 3 September, precipitation likely reduced male and female captures at 50 cm relative to the more sheltered placement at 30 cm.

In 2002, male ($F = 37.60$; df = 6, 98; $P<0.0001$) captures were significantly higher on traps placed between 20 cm below and 20 cm above the crop canopy, than on traps at lower or higher positions (Table 4). Female ($F = 32.80$; df = 6, 104; $P<0.0001$) captures were significantly higher on traps placed below the crop canopy than on traps placed at or above the crop canopy. Total ($F = 17.08$; df = 6, 98; $P<0.0001$) captures were highest on traps placed at canopy height or below. There were significant date*treatment interactions for males ($F = 8.59$; df = 6, 98; $P<0.0001$) and total ($F = 3.26$; df = 6, 98; $P = 0.0058$) captured. These interactions were apparently due to low insect captures on 1 August, leading to lack of a significant treatment effect for males ($F = 0.65$; df = 4; 98; $P = 0.6342$). As patterns of capture on the remaining dates (14 August and 17 September) were almost identical to those for all dates combined, pooled data are presented here.

Discussion and Conclusions

The effect of colour on specific behaviours of insects is not well known, but it is generally accepted that attractive colours elicit more alighting by insects (Bernays and Chapman 1994). Adult pea leafminer, both male and female, are attracted to yellow and green sticky traps but not to white, blue, red and violet traps. Previous studies of other leafminers, as well as other dipterans, have shown an attraction for yellow and green, with yellow being the most common colour when sticky cards are used for monitoring (Chandler 1981; Affeldt et al. 1983; Harris and Miller 1983; Zoebisch and Schuster 1990; Jones and Schreiber 1994; Degen and Städler 1996). It is uncertain why so many insects respond strongly to yellow; however, these wavelengths are in the range of 560 to 580 nm and are not far from the peak sensitivity of an insect's green sensitive pigment (540 nm). The reflectance intensity of peak yellow wavelengths between 560 and 580 are also generally much higher than the peak wavelengths reflected by green pigments, and it has been hypothesized that yellow simply represents a 'supernormal', or more highly attractive version of green to certain insects (Bernays and Chapman 1994). In contrast, *Delia antiqua*, the onion fly, is more attracted to white painted surfaces than yellow cardboard in the field

TABLE 3. Effect of trap height on the number of male, female, and total adult pea leafminer, *Liriomyza huidobrensis*, captured on yellow sticky card traps in celery in 2001. The mean crop canopy height was 65 cm.

			Mean (± SE) Number of Pea Leafminer Adults Captured[1]		
Date	**Height above ground (cm)**	**n**	**Male**	**Female**	**Total**
3 September 2001	90	9	7.11 ± 1.36 **e**	3.78 ± 0.64 **d**	10.89 ± 1.58 **e**
	70	9	18.89 ± 1.30 **d**	9.44 ± 1.17 **c**	28.33 ± 1.94 **d**
	50	9	76.56 ± 7.71 **b**	57.22 ± 2.80 **a**	133.78 ± 8.30 **b**
	30	9	175.56 ± 24.45 **a**	88.44 ± 8.70 **a**	264.00 ± 32.50 **a**
	10	9	30.67 ± 8.79 **c**	27.89 ± 2.34 **b**	58.56 ± 9.49 **c**
6 September 2001	90	9	11.11 ± 1.47 **c**	9.78 ± 1.41 **c**	20.89 ± 2.24 **c**
	70	9	33.11 ± 2.93 **b**	31.56 ± 3.29 **b**	64.67 ± 5.25 **b**
	50	9	141.67 ± 16.30 **a**	115.67 ± 11.53 **a**	257.33 ± 21.86 **a**
	30	9	109.56 ± 15.65 **a**	108.78 ± 6.12 **a**	218.33 ± 17.34 **a**
	10	9	11.78 ± 2.68 **c**	37.22 ± 5.55 **b**	49.00 ± 7.75 **b**

[1]Means in the same column followed by the same letter are not significantly different, ANOVA and Tukey's HSD comparisons of means, $\alpha = 0.05$.

TABLE 4. Effect of trap placement relative to the celery canopy on the number of male, female, and total adult pea leafminer, *Liriomyza huidobrensis*, captured on yellow sticky card traps in 2002. Data for three dates combined (1 and 14 August, and 17 September 2002; mean crop height was 30, 50 and 70 cm, respectively).

		Mean (± SE) Number of Pea Leafminer Adults Captured[1]		
Position relative to crop height	n	Male	Female	Total
60 cm above	8	0.50 ± 0.27 **b**	0.12 ± 0.12 **d**	0.63 ± 0.26 **c**
40 cm above	16	0.81 ± 0.43 **b**	0.19 ± 0.14 **d**	1.00 ± 0.56 **c**
20 cm above	24	4.79 ± 1.29 **a**	2.83 ± 0.93 **c**	7.62 ± 2.11 **b**
At crop height	24	13.79 ± 3.69 **a**	6.59 ± 1.75 **b**	20.29 ± 5.25 **a**
20 cm below	24	11.76 ± 4.00 **a**	16.20 ± 3.86 **a**	27.96 ± 5.51 **a**
40 cm below	16	0.87 ± 0.31 **b**	13.47 ± 2.97 **a**	13.33 ± 2.95 **a**
60 cm below	8	0 ± 0 **b**	14.50 ± 3.79 **a**	14.50 ± 3.79 **a**

[1]Means in the same column followed by the same letter are not significantly different, ANOVA and Tukey's HSD comparisons of means, $\alpha = 0.05$.

(Vernon and Bartel 1985) and insects attacking the flowers of plants, such as *Frankliniella occidentalis*, are frequently attracted to blue sticky traps (Gillespie and Vernon 1990).

In 2002, captures of adult pea leafminers were numerically higher on traps that allowed for the transmission of light as opposed to opaque traps of the same colour. Translucent traps appear brighter than their opaque counterparts, due in part to the combined reflectance of yellow wavelengths from, and the transmission of yellow wavelengths through, the trap.

In the 2001 trap colour experiment, approximately twice as many males as females were captured, while more than three times as many females as males were trapped in 2002. This result is likely due to the placement of traps within the canopy (top in 2001 and middle in 2002) rather than a reflection of the sex ratio present in the field. In 2001, the sex ratios of the trap height (1 : 0.43 males to females) and colour (1 : 0.80) experiments were more similar than in 2002, when the sex ratio in the colour experiment (1 : 4.15) was more strongly biased towards females than height experiment (1 : 1.18) for three similar dates. Even though sex ratios of adults emerging from colony-reared pupae indicate a 1:1 sex ratio (Parrella 1987), Jones and Parrella (1986) captured 83.5% males and 16.5% females in a greenhouse when traps were placed 0.3 m above the canopy. In potatoes, about twice as many females as males were caught on sticky traps 10 cm above the ground, but relatively equal sex ratios were found at heights up to 70 cm, which was 20 cm above the crop canopy (Weintraub and Horowitz 1996).

In the trap height experiments, captures of female pea leafminers were highest when traps were positioned within the celery canopy. Male pea leafminers were most

frequently captured on traps that were located within 20 cm above or below the top of the canopy despite the mean height of the crop changing over 40 cm throughout the duration of the experiment. In contrast, captures of male *Liriomyza* spp. were highest in the middle and lower portions of a tomato canopy in a study by Zehnder and Trumble (1984), which may be related to canopy architecture. Increased captures of pea leafminer males in the upper portion of the celery canopy may be explained by high flight activity as they actively search for food and mates, while females spend more time on leaves for oviposition. This interpretation is supported by the finding that significantly more pea leafminer larvae were found in cucumber leaves within the lower canopy than at higher positions on the plant (Abou-Fakhr Hammad and Nemer 2000). Our findings suggest that trap height studies should be designed, and recommendations expressed, in relation to the height of the crop canopy rather than height above the ground to more accurately reflect insect behaviour.

Combined captures of male and female pea leafminer adults were highest in the middle portion of the celery canopy. These results correspond with other studies on the spatial distribution of *Liriomyza* within plants when sex is not considered. In potato, more pea leafminer were captured at or just below crop height than closer to the ground (Weintraub and Horowitz 1996). More *L. trifolii* and *L. sativae* adults were captured by placing cards at low to middle canopy heights in tomatoes and peppers (Zehnder and Trumble 1984; Chandler 1985; Zoebisch and Schuster 1990), possibly indicating host-dependent spatial distributions. There are several reasons for high captures of adult *Liriomyza* in the middle of the crop canopy. Adult longevity is prolonged at cooler temperatures (Parrella 1987), and due to an absence of direct sunlight, temperatures are cooler within the crop canopy than above it. Maximum daily air temperatures at the time of the experiment in 2001 were 27°C with temperatures frequently rising above 30°C in 2002. Female fecundity of *L. trifolii* is greatly reduced as temperatures approach 35°C, with maximum fecundity at 30°C (Leibee 1984). Female pea leafminers may remain within the crop canopy in order to maximize their fitness. Larvae developing lower within the canopy may also be protected from temperature extremes and parasitoids by the dense foliage.

In the Holland Marsh region of Ontario, pea leafminer populations remain low through July and August but rapidly reach economically damaging levels from early September to October (Martin et al. 2005). Adult pea leafminer have a high attraction to sticky cards that reflect through the yellow portion of the spectrum, as opposed to blue. Translucent yellow sticky cards placed 20 cm below the top of the crop canopy are most efficient at capturing both male and female adult pea leafminer in celery. Although sticky trap captures cannot as yet be used to adequately time chemical sprays to target larvae, they can be used as an indicator of pea leafminer presence and movement of adults throughout a field (Zehnder and Trumble 1984; Heinz and Chaney 1995). In addition, a rapid increase in adults on sticky traps can be used to herald the need for more extensive larval monitoring within the crop.

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References

Abou-Fakhr Hammad, E. M. and N. M. Nemer. 2000. Population densities, spatial pattern and development of the pea leafminer (Diptera: Agromyzidae) on cucumber, swiss chard, and bean. Journal of Agricultural Science 134: 61-68.

Affeldt, H. A., R. W. Thimijan, F. F. Smith, and R. E. Webb. 1983. Response of the greenhouse whitefly (Homoptera: Aleyrodidae) and the vegetable leafminer (Diptera:Agromyzidae) to photospectra. Journal of Economic Entomology 76: 1405-1409.

Bernays, E. A. and R. F. Chapman. 1994. Host Plant Selection by Phytophagous Insects. Chapman & Hall, Inc. New York. 312pp.

Chandler, L. D. 1981. Evaluation of different shapes and colour intensities of yellow traps for use in population monitoring of Dipterous leafminers. Southwestern Entomologist 6: 23-27.

Chandler, L. D. 1985. Flight activity of *Liriomyza trifolii* (Diptera: Agromyzidae) in relationship to placement of yellow traps in bell pepper. Journal of Economic Entomology 78: 825-828.

Degen, T. and E. Städler. 1996. Foliar form, colour and surface characteristics influence oviposition behaviour of the carrot fly. Entomologia Experimentalis et Applicata 83: 99-112.

Gillespie, D. R. and R. S. Vernon. 1990. Trap catch of western flower thrips (Thysanoptera: Thripidae) as affected by colour and height of sticky traps in mature greenhouse cucumber crops. Journal of Economic Entomology 83: 971-975.

Harris, M. O. and J. R. Miller. 1983. Colour stimuli and oviposition behaviour of the onion fly, *Delia antiqua* (Meigen) (Diptera: Anthomyiidae). Annals of the Entomological Society of America 76: 766-771.

Heinz, K. M. and W. E. Chaney. 1995. Sampling for *Liriomyza huidobrensis* (Diptera: Agromyzidae) larvae and damage in celery. Environmental Entomology 24: 204-211.

Johnson, M. W., E. R. Oatman, and J. A. Wyman. 1980. Effects of insecticides on populations of the vegetable leafminer and associated parasites on summer pole tomatoes. Journal of Economic Entomology 73: 61-66.

Jones, V. P. and M. P. Parella. 1986. The movement and dispersal of *Liriomyza trifolii* (Diptera: Agromyzidae) in a chrysanthemum greenhouse. Annals of Applied Biology 109: 33-39.

Jones, C. J. and E. T. Schreiber. 1994. Colour and height affects oviposition site preferences of *Toxorhynchites splendens* and *Toxorhynchites rutilus rutilus* (Diptera: Culicidae)

in the laboratory. Environmental Entomology 23: 130-135.

Leibee, G. L. 1984. Influence of temperature of development and fecundity of *Liriomyza trifolii* (Burgess) (Diptera: Agromyzidae) on celery. Environmental Entomology 13: 497-501.

Levins, R. A., S. L. Poe, R. C. Lettell, and J. P. Jones. 1975. Effectiveness of a leafminer control program for Florida tomato production. Journal of Economic Entomology 68: 772-774.

Martin, A. D., R. H. Hallett, M. K. Sears, and M. R. McDonald. 2005. Overwintering ability of *Liriomyza huidobrensis* (Blanchard) (Diptera: Agromyzidae), in southern Ontario, Canada. Environmental Entomology 34: 743-747.

McDonald, M. R., M. K. Sears, T. Clarke, J. Chaput, and S. A. Marshall. 2000. Pea leafminer, a new pest of leafy vegetables in Ontario, Canada. Hortscience 35: 392.

Parrella M. 1987. Biology of *Liriomyza*. Annual Review of Entomology 32: 201-224.

Poe, S. L., P. H. Everett, D. J. Schuster, and C. A. Musgrave. 1978. Insecticidal effects on *Liriomyza sativae* larvae and their parasites on tomato. Journal of the Georgia Entomological Society 13: 322-327.

SAS Institute. 1999. SAS for Windows, ver. 8.1. SAS Institute Inc. Cary, NC.

Spencer K. A. 1973. Agromyzidae (Diptera) of Economic Importance. Series Entomologica, The Hague 9:1-144.

Vernon, R. S. and D. L. Bartel. 1985. Effect of hue, saturation and intensity on colour selection by the onion fly, *Delia antiqua* (Meigen) (Diptera: Anthomyiidae) in the field. Environmental Entomology 14: 210-216.

Weintraub, P. G. and A. R. Horowitz. 1995. The newest leafminer pest in Israel, *Liriomyza huidobrensis*. Phytoparasitica 23:177-184.

Weintraub, P. G. and A. R. Horowitz. 1996. Spatial and diel activity of the pea leafminer (Diptera: Agromyzidae) in potatoes, *Solanum tuberosum*. Environmental Entomology 25:722-726.

Zehnder, G. W. and J. T. Trumble. 1984. Spatial and diel activity of *Liriomyza* species (Diptera: Agromyzidae) in fresh market tomatoes. Environmental Entomology 13:1411-1416.

Zoebisch, T. G. and D. J. Schuster. 1990. Influence of height of yellow sticky cards on captures of adult leafminer (*Liriomyza trifolii*) (Diptera: Agromyzidae) in staked tomatoes. Florida Entomologist 73: 505-507.

NEW RECORDS OF NATIVE AND INTRODUCED ACULEATE HYMENOPTERA FROM ONTARIO, WITH KEYS TO EASTERN CANADIAN SPECIES OF *CERCERIS* (CRABRONIDAE) AND EASTERN NEARCTIC SPECIES OF *CHELOSTOMA* (MEGACHILIDAE)

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Abstract *J. ent. Soc. Ont.* 136: 37–52

The Palaearctic *Ancistrocerus gazella* (Vespidae) and *Spilomena troglodytes* (Crabronidae) are recorded for the first time from the Nearctic region based on material from Ontario (both species) and the northeastern United States (*A. gazella*). Seven species are recorded for the first time from Canada (C), one from eastern Canada (eC) and two from the eastern Nearctic (eN). Sierolomorphidae: *Sierolomorpha nigrescens* (eN); Sphecidae: *Isodontia elegans* (eN), *I. philadelphica* (C); Crabronidae: *Tachysphex punctifrons* (eC), *Ectemnius paucimaculatus* (C), *Cerceris bicornuta* (C); Colletidae: *Hylaeus hyalinatus* (C); Megachilidae: *Chelostoma campanularum* (C), *Ch. rapunculi* (C), *Hoplitis anthocopoides* (C). The recently recorded *Stictia carolina* (Crabronidae) is confirmed as established in southern Ontario. A key to the twenty eastern Canadian species of the genus *Cerceris* (Crabronidae) is provided, separating for the first time males of several species in the *echo*, *clypeata*, and *nigrescens* species groups. The three eastern Nearctic species of *Chelostoma* (Megachilidae) are also keyed.

Introduction

Despite substantial recent faunistic work many Ontario Aculeata families still remain relatively poorly documented. Until recently less than 59% of Ontario spheciform wasps had been recorded (Buck 2004). Unpublished data show similar ratios for other families of aculeate wasps, e.g., Vespidae 64% (Buck et al., in prep.), Pompilidae 60%, Mutillidae 33% (Buck unpubl.). The present paper updates the recently published checklist of Ontario spheciform wasps (Buck 2004) by adding six species of Sphecidae and Crabronidae, which brings the provincial total up to 284 species. Five new records in four other families (Sierolomorphidae, Vespidae, Colletidae, Megachilidae) are also presented.

Species inventories are important because the Ontario Hymenoptera fauna is in

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a constant state of flux. Faunal change is being effected by various causes such as local extirpations, introductions of exotic species (e.g. Smith 1991; Paiero and Buck 2004; Romankova 2004; Buck 2004, 2005), and natural range extensions. The present paper provides examples for the latter two categories. As documented recently for three groups of solitary wasps (Crabronidae, Pompilidae, Vespidae: Eumeninae; see Buck 2005), the increase in the number of exotic aculeate species is due mostly to introductions of cavity-nesting species (including mud daubers), whereas the ground-nesting fauna has remained largely unaffected. Six introduced species that are newly recorded in this paper, as well as several previously recorded introduced bees (Paiero and Buck 2004; Romankova 2004; Smith 1991) are likewise cavity-nesters or construct free-standing mortar nests. Some of the newly recorded species have been present in Ontario (or North America) for a long period of time without being noticed (either due to misidentification or because old material was identified only recently). Range extensions of native species are also often overlooked or detected with delay due to a lack of consistent sampling and a shortage of taxonomic expertise. The suspected case of a northward range extension into Ontario of one of the largest and most conspicuous spheciform wasps in North America (the 'horse guard', *Stictia carolina*, Crabronidae) was reported earlier (Buck 2004). New data provided in this paper now suggest that the species has in fact become established in Ontario.

Materials and Methods

All specimens, unless noted otherwise, are deposited in the University of Guelph Insect Collection, Department of Environmental Biology, Guelph, Ontario.

Acronyms of depositories: AMNH – American Museum of Natural History, New York, New York; CNCI – Canadian National Collection of Insects, Ottawa, Ontario; GAM – private collection of Parker Gambino, Brewster, New York; GUS – private collection of Josef Gusenleitner, Linz, Austria; ROME – Royal Ontario Museum, Toronto, Ontario.

Abbreviations: MOD – mid ocellar diameter.

Sierolomorphidae

***Sierolomorpha nigrescens* Evans, 1961**

CANADA, Ontario: Thunder Bay Distr., 4♂, ♀, Sleeping Giant Provincial Park, Marie Louise Lake Campground, 48°21'47"N, 88°47'53"W, 9–14 July 2002, forest trail, white pan traps, M. Buck.

Recorded for the first time from the eastern Nearctic. Previously, the species was known from Saskatchewan west to the Yukon and south to California, Arizona, and Colorado (Evans 1961). Evans (l.c.) suspected that *S. nigrescens* might be a western subspecies of *S. canadensis* (Provancher). He mentions a range overlap between the two species, which is incompatible with the hypothesis of subspecies status. The biology of Sierolomorphidae is unknown. Most species appear to be associated with wooded areas and might be parasitoids of wood-boring insects.

Vespidae

***Ancistrocerus gazella* (Panzer, 1798)**

CANADA, Ontario: York Reg., ♀, Etobicoke, 16 August 1995, garden, B. Larson. **Peel Reg.**, ♀, Cooksville, 17 June 1993, field vegetation, R. Krupke. **Wellington Co.**, ♀, Guelph, 6 October 1992, field, D. Bennett; ♀, Guelph, Speed River, 7 October 1997, sweep net, R. Vincent; Guelph, University Campus, ♂, 31 August 2001, S. M. Paiero, ♀, 3–5 September, ♀, 6 September 2002, M. Buck, ♂, ♀, 16 August, ♂, 25 August, ♀, 26 August, ♀, 30 August, 2♀, 1 September, 2♀, 3 September 2004, M. Buck. **Halton Reg.**, ♀, Milton, Derry Rd. & 4th Line, 43°31'31"N, 79°50'25"W, 5 August 2002, S. M. Paiero. **Welland Co.**, 2♀, Thorold, 21 August 1983, M. D. Forward. **UNITED STATES, Massachusetts**: ♀, Cape Cod, 13 August 1978, W. A. Attwater. **New York**: ♀, New York, Central Park, 1 October 1961, P. H. Arnaud (AMNH); ♀, Kings Co., Brighton Beach area, 8 August 1962, S. H. Hessel and R. B. Tarsy (AMNH); 1 specimen, Newburgh, Fostertown, 26 June 1967, P. P. Babiy (GUS*). **New Jersey**: ♀, Bergen Co., Closter, 26 June 1962, J. G. Rozen et al. (AMNH). **Delaware**: 1 specimen, Wilmington, 11 June 1974, P. P. Babiy (GUS*). (*data kindly provided by J. Gusenleitner; material not examined by the authors).

The oldest Nearctic specimen of this Palaearctic species examined was collected in New York in 1961. Due to its similarity to another introduced Palaearctic species, *A. parietum* (L.), which has been known from eastern North America for a long time, *A. gazella* was overlooked for almost half a century. For identification Gusenleitner's (1995) key to central and southern European *Ancistrocerus* was used. *Ancistrocerus gazella* differs from *A. parietum* by the following characters: transverse carina of tergum 1 with small median incision only (with deep, V-shaped incision in *parietum*), and metanotum with complete yellow band (in some males divided medially or absent; black or with small, evanescent yellow spots in *parietum*). The Palaearctic range of *A. gazella* includes most of Europe (except northern Scandinavia) east to the Caucasus, North Africa (Morocco), and Madeira (Blüthgen 1961). Like the closely related *A. parietum*, it nests in a great variety of natural and man-made cavities including hollow stems, borings in wood, hollows in brick-and-mortar walls, or metal rails (Blüthgen l.c.). In central Europe the species has two generations (Blüthgen l.c.). The flight period in Ontario is similar, and probably includes two generations as well.

Sphecidae

***Isodontia elegans* (F. Smith, 1856)**

CANADA, Ontario: Essex Co., ♀, La Salle, Brunet Park, 29 July 2005, S. M. Paiero. **UNITED STATES, New York** (data kindly provided by P. Gambino; material not examined by the authors): Bronx Co., Harris Park Annex, 2♀, 19 July 1995, ♂, ♀, 16 July 1996, P. Gambino (GAM); Bronx Co., ♂, East 211th Street at Woodlawn Cemetery, 12 August 1997, P. Gambino (GAM); Bronx Co., Van Cortlandt Park at Gunhill Road, ♀, 6 June 2000, ♂, 27 June 2001, 2♂, ♀, 3 July 2005, P. Gambino (GAM); Westchester Co., ♀, Croton Point Park, 19 August 1999, P. Gambino (GAM).

First published records of *I. elegans* from the eastern Nearctic region. The natural range of this species extends from British Columbia south to California, Texas and northern Mexico (Bohart and Menke 1963). The easternmost previously published records are from western Nebraska and east-central Texas. Besides the material listed above, two eastern Nearctic records of *I. elegans* have been posted on an amateur entomological website on the internet. One record (supplemented by an image of a correctly identified *I. elegans*) is from West Chicago Prairie, DuPage Co., Illinois on 2 July 2005 (Marlin 2005). Another contributor to the website mentions collecting the species "in Cincinnati [Ohio] in the 1990s" (Eaton 2005). *Isodontia elegans* is recognised easily by the brownish colour of the metasoma, and there is therefore no reason to doubt the identity of the mentioned material. The occurrence of this species in the eastern Nearctic is probably due to accidental introduction. Because of their nesting habits (in borings in wood, stems, etc.), species of this genus are prone to be introduced accidentally to other geographic areas. This has also happened to the closely related eastern Nearctic species *I. mexicana* (Saussure), which was accidentally introduced to southern Europe and Hawaii (Bohart and Menke 1963; Bitsch et al. 1997). Examples of western-eastern Nearctic introductions are rare in aculeate wasps. Besides the western *Trypoxylon bidentatum* Fox, which might have become established in Ontario (see Buck 2004), *I. elegans* appears to be the only example for this introduction pattern.

***Isodontia philadelphica* (Lepeletier, 1845)**

CANADA, Ontario: Kent Co., ♂, Rondeau Provincial Park, South Point Trail East, 42°15'35"N, 81°50'53"W, sandy savannah, visiting *Melilotus albus* Medikus flowers, 28 July 2005, M. Buck.

First record for Canada. Harrington (1902) and Walker (1913) erroneously recorded the species from Ontario (Buck 2004). The previously known range extends from Connecticut, New York, and Illinois south to Florida and west to California (Bohart and Menke 1963). *Isodontia philadelphica* is easily distinguished from other species in the genus by the mainly dark pubescence of the body.

Crabronidae

***Spilomena troglodytes* (Vander Linden, 1829)**

CANADA, Ontario: Wellington Co., ♀, Guelph, University of Guelph Campus, 16 August 2004, on *Solidago* flowers, M. Buck. Other material examined: **FINLAND**: ♂, ♀, Tavastia australis, Janakkala, 5 July 2002, swept from *Salix fragilis* L., V. Vikberg.

Spilomena troglodytes is a trans-Palaearctic species (Pulawski 2005) that is recorded here for the first time from North America. The species was identified using Palaearctic keys by Vikberg (2000), Dollfuss (1986), and Lomholdt (1975) and compared to authoritatively identified material from Finland that was kindly provided by V. Vikberg. In Bohart and Smith's (1995) key to Nearctic *Spilomena* species, *S. troglodytes* runs to couplets 15 (females of *S. pusilla* (Say) and *S. hainesi* N. Smith) and 20 (males of *S. barberi* Krombein and *S. pusilla*). The female of *S. troglodytes* is distinguished from *S. pusilla* by the apically compressed tergum 6 which bears a median carina (or double carina) in its apical third (tergum rounded and ecarinate in *S. pusilla* and *S. barberi*, undescribed

for the Californian *S. hainesi*). From *S. hainesi* it can be separated by the short basal flagellomeres (longer than broad in *S. hainesi* according to Bohart and Smith (1995)). The male differs from *S. pusilla* by the less extensive yellow facial markings (not surrounding antennal bases dorsally); both sexes differ from *S. barberi* by the scarcely pubescent apical portions of terga 3–6 (pubescence fairly dense and in a clearly defined band in *S. barberi*). *Spilomena troglodytes* nests in borings in wood, preferably those made by anobiid beetles, and in thatched roofs; it provisions its brood with nymphal Thysanoptera (Lomholdt 1975). The species was probably introduced accidentally to North America with timber or other substrates containing nests.

***Tachysphex punctifrons* Fox, 1891**

CANADA, Ontario: Leeds and Grenville Co., ♂, Lake Opinicon, Perth Road Village, Queens University Biological Station, 44°33'57"N, 76°19'31"W, 1–6 August 2005, L. Best.

Recorded for the first time from eastern Canada. Western Canadian records are from Manitoba to Alberta. In the eastern United States the species occurs along the Atlantic Seaboard from Massachusetts to Florida and west to North Dakota, Idaho, Utah, and New Mexico (Pulawski 1988). The species is rare in the Great Lakes region (F. E. Kurczewski, in litt.), where it has been recorded from Michigan, Illinois, Wisconsin, and Minnesota (Pulawski 1988).

***Ectemnius paucimaculatus* (Packard, 1866)**

CANADA, Ontario: Kent Co., ♂, Rondeau Provincial Park, Marsh Trail North, 11 July 2005, visiting flowers of *Daucus carota* L., M. Buck.

Recorded for the first time from Canada. This species was wrongly recorded from the Ottawa area by Harrington (1902) (see Buck 2004). It is very similar to *E. stirpicola* (Packard) with which it has been confused. However, the shape of the clypeus (illustrated by Bohart and Kimsey 1979) is a very reliable diagnostic character despite the quite subtle difference between the two species. The colouration of tergum 5, another character mentioned by Bohart and Kimsey (l.c., couplet 21: with a pair of yellow spots in *stirpicola*, without spots in *paucimaculatus*) has proven unreliable. The senior author has examined several *E. stirpicola* from Ontario (in CNCI) that lack yellow spots on tergum 5, and in some melanistic specimens the yellow markings of the metasoma are reduced to a single pair of spots on tergum 2. *Ectemnius paucimaculatus* has been recorded previously from Illinois and New York south to Florida (Krombein 1979).

***Stictia carolina* (Fabricius, 1793)**

CANADA, Ontario: Kent Co., ♂, Rondeau Provincial Park, South Point Trail East, 42°15'35"N, 81°50'53"W, dunes, visiting flowers of *Melilotus albus*, 28 July 2005, M. Buck.

This large and conspicuous species was recorded recently for the first time from Canada based on a single male from Point Pelee, Ontario (Buck 2004). At the time it was unclear whether the recorded specimen was just a straggler or whether the species had recently expanded its range into southern Ontario. No further collecting was done at Point Pelee since the first discovery but the new finding of *Stictia carolina* approximately 65 km

ENE of Point Pelee indicates that this species has apparently become established along the western part of Lake Erie in southern Ontario.

***Cerceris bicornuta* Guérin, 1845** (Fig. 1)

CANADA, Ontario: Lambton Co., ♀, Walpole Island, Chief's Road, sand pits, 42°39'39"N, 82°29'41"W, 8 August 2005, dug out from ground burrow, S. M. Paiero. **Essex Co.**, ♀, Windsor, Broadway Park, 28 July 2005, M. D. Bergeron.

First record from Canada. In the United States the species has a transcontinental distribution from Massachusetts, southern New York, lower Michigan and Illinois south to Florida and west to California and Oregon (Scullen 1965). Because of the unusual colouration of the female and male morphology (see Fig. 1 and key below) this species is easily recognisable. With twenty species, *Cerceris* is the largest genus of spheciform wasps in eastern Canada but most species are difficult to identify with the current literature. Scullen's (1965) revision of the genus provides good illustrations of certain diagnostic features but his key is often misleading and difficult to use for a non-expert. Furthermore, males in several species groups (*arelate-dentifrons*, *atramontensis-clypeata-halone-prominens*, *echo-finitima*) have never been separated. With recent renewed interest in the genus (Marshall et al. 2005) we take the opportunity to provide a novel key to the eastern Canadian species of *Cerceris* that remedies these problems.

FIGURE 1. Female *Cerceris bicornuta* from Windsor, Ontario, July 2005 (photo by S. A. Marshall).

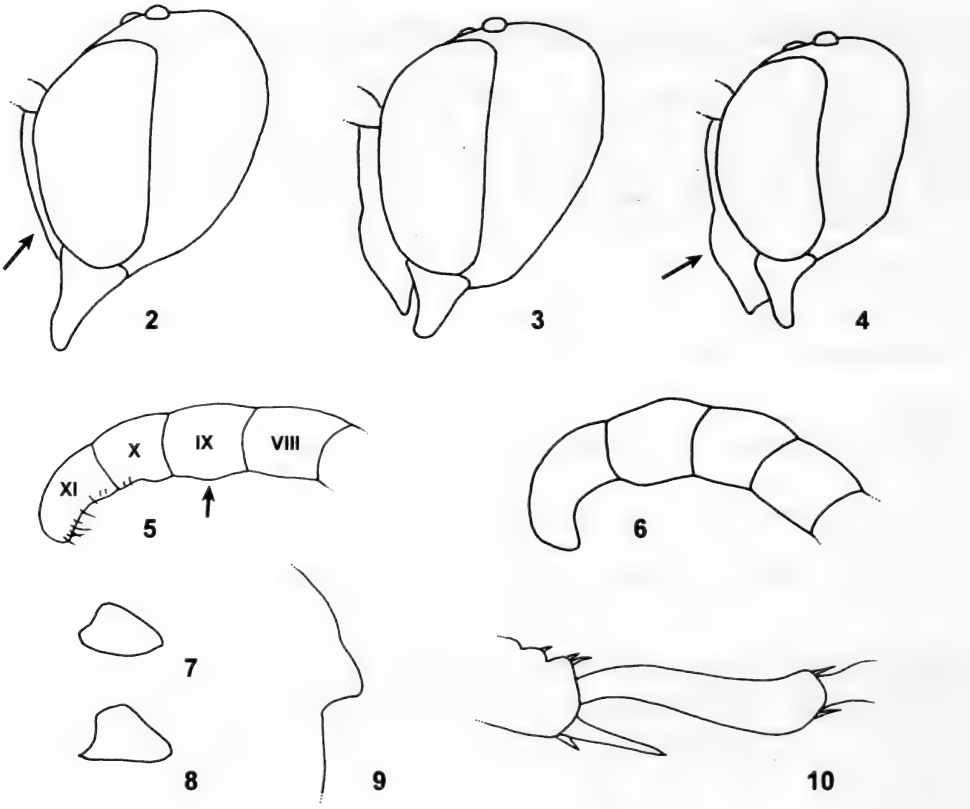
Key to the eastern Canadian species of *Cerceris* Latreille

Notes. Four species from the northeastern United States might be found in Canada in the future but are not included in the key: *C. alaope* Banks (Massachusetts, southern New York), *C. compar* Cresson (distributed widely throughout New England states, Pennsylvania, Ohio, Michigan, Minnesota), *C. jucunda* Cresson (New York), and *C. mandibularis* Patton (southern New York, southern Pennsylvania). The species marked by asterisk (*) are not known from any other Canadian province besides Ontario. It should be noted that colouration shows geographic variation in most species. The present key is designed for eastern Canada and adjacent regions, and some colour characters will not necessarily work for southern or western specimens of the species included here.

Females

(Antenna with ten flagellomeres, metasoma with six apparent segments.)

1. Clypeal process with broadly lamellate apex. Scutellum with a pair of yellow spots 2
– Clypeal process not lamellate apically, variably developed, in some specimens very small and virtually absent. Scutellum usually black, rarely with complete yellow band or a pair of yellow spots or largely ferruginous.....3
2. Width of lamellate portion of clypeal process less than length of scape; lamella inserted at level of lower eye margin. Metanotum black.....***C. rufopicta*** F. Smith
– Width of lamellate portion of clypeal process ca. 1.5x length of scape; lamella inserted far above level of lower eye margin. Metanotum with complete yellow band.....***C. compacta*** Cresson*
3. Tegula conspicuously humped (as in Fig. 7) with coarsely punctate summit *and/or* mesopleuron with distinct, tooth-like ventrolateral tubercle near middle (Fig. 9). Pygidial plate narrowed towards base; basal width at most slightly greater than half maximum width. Scutellum with a pair of yellow spots or complete yellow band..... 4
– Tegula moderately convex and usually smooth, rarely with a few scattered coarse punctures on summit. Mesopleuron rounded ventrolaterally, in some specimens with minute angle. Pygidial plate variable. Scutellum usually black.....7
4. Clypeal process weakly trilobate, middle lobe broad, with slightly convex apex. Tegula evenly convex, not humped, with smooth summit. Metanotum black. Yellow fasciae on terga 2 and 4 complete, broadly interrupted on 3..... .....***C. kennicottii*** Cresson*
– Clypeal process bilobate or bidentate, its apical margin slightly to conspicuously emarginate between corners. Tegula distinctly humped, with coarsely punctate summit. Metanotum with complete yellow band. Yellow fasciae on terga 2–4 complete.....5
5. Clypeal process narrow (ca. 1.5x MOD), with sharp median incision. Tergum 1 largely ferruginous. Ventrolateral tubercle of mesopleuron poorly developed, apical angle in anterior view much greater than 90°. [Subantennal sclerite and clypeus black.].....***C. crucis*** Viereck & Cockerell*



FIGURES 2–10. Diagnostic features of *Cerceris* adults. Male head, lateral view: 2 – *C. halone*, 3 – *C. clypeata*, 4 – *C. occipitomaculata*. Male flagellomeres VIII–XI, dorsal view: 5 – *C. atramontensis* (arrow pointing to posterior swelling of flagellomere), 6 – *C. bicornuta*. Male tegula, posterior view: 7 – *C. echo*, 8 – *C. finitima*. Ventrolateral tubercle of female mesopleuron, anteroventral view: 9 – *C. echo*. Male hind basitarsus, posterodorsal view: 10 – *C. bicornuta*.

– Clypeal process broad (> 2 MOD), very shallowly emarginate. Tergum 1 black, usually marked with yellow. Tubercle of mesopleuron prominent, apical angle in anterior view ≤ 90° (Fig. 9).....6

6. Subantennal sclerite and clypeus almost completely yellow. Clypeus essentially flat above process; apex of process extending ventrally to level of clypeal margin.....***C. finitima*** Cresson*

– Subantennal sclerite and clypeus black, the latter rarely with small median yellow spot. Clypeus with median convexity above process; apex of process ending short of level of ventral clypeal margin.....***C. echo*** Mickel*

7. Clypeal process virtually absent.....8

– Clypeal process prominent, of variable shape.....9

8. Disc of clypeus evenly convex, with a pair of tiny tubercles just above apical margin. Antennal flagellomeres (VI–)VII–X with linear tyli. Propodeum black. Metasomal terga black except for broad yellow fascia on tergum 2 and in some specimens small lateral spots on tergum 3. Wing strongly infuscated. Large species, body length ca. 15 mm.....***C. fumipennis*** Say*
– Clypeus with an indistinct, curved, ridge-like swelling near middle, area below swelling flattened. Antennal flagellomeres without tyli. Propodeum with a pair of yellow spots. Metasoma with subequal yellow fasciae on terga 2–5. Wing weakly infuscated. Smaller, length ca. 10 mm.....***C. deserta*** Say
9. Clypeal process developed as low, conical, median tubercle.....10
– Clypeal process not conical, its apex emarginate or truncate (in some specimens only narrowly) in dorsal view.....11
10. Clypeal process somewhat flattened dorsoventrally and slightly deflected downward at apex (lateral view). Inner margin of mandible with low and ill-defined teeth, not notched. Scutellum black, metanotum yellow. Metasomal terga 2–5 with subequal yellow fasciae.....***C. nitidoides*** Ferguson
– Clypeal process neither dorsoventrally flattened nor deflected, apex rectangular in lateral view. Second mandibular tooth very enlarged, inner margin of mandible deeply notched just distal of tooth. Scutellum yellow-banded, metanotum black. Tergum 2 black, tergum 3 with broad yellow fascia, terga 4 and 5 with narrow yellow fasciae.....***C. insolita*** Cresson*
11. Yellow fascia of tergum 2 distinctly wider than on following terga.....12
– Yellow fasciae of metasomal terga 2–5 subequal.....16
12. Head, pronotum, and propodeum with ferruginous markings; scutellum and metasoma largely ferruginous. Terga 3–5 without yellow fasciae. Pygidial plate about half as wide at base than at middle.....***C. bicornuta*** Guérin*
– Body without ferruginous markings. Terga 3–5 with yellow apical fasciae. Pygidial plate as wide at base as at middle.....13
13. Clypeal process (measured from base of clypeus to apex of process along midline) at least as long as scape. Clypeus with yellow spots laterally (exceptionally absent).....***C. clypeata*** Dahlbom
– Clypeal process shorter than scape. Clypeus often without yellow spots.....14
14. Clypeal margin with a pair of very prominent and stout paramedian teeth bordering deep median emargination (depth of depression equals diameter of scape). Edge of clypeal process strongly curved (often almost semicircularly) in anteroventral view. Clypeus with yellow markings laterally and medially below process.....***C. halone*** Banks
– Paramedian teeth of clypeal margin less robust and less prominent, area between them moderately emarginate (depth of emargination at most half diameter of scape). Edge of clypeal process usually straight to slightly curved in anteroventral view. Clypeus black laterally, rarely with median yellow spot below process.....15
15. Apical corners of clypeal process as far apart as centres of antennal sockets. Process projecting clearly less than diameter of scape beyond level of flattened lower part of clypeus (lateral view). Widespread.....***C. atramontensis*** Banks

– Apical corners of clypeal process as far apart as lateral margins of antennal sockets. Process projecting by at least diameter of scape beyond level of flattened lower part of clypeus (Ottawa area, one record only).....***C. prominens*** Banks*

16. Clypeal margin without median tooth. Rarely collected species.....17
– Clypeal margin with low, often rectangular, median tooth.....18

17. Clypeal margin with one pair of teeth that are twice as far apart as antennal sockets; margin between teeth straight. Clypeal process parallel-sided and broad, its apical corners further apart than lateral margins of antennal sockets. Scutum dull between punctures.....***C. occipitomaculata*** Packard*
– Clypeal margin with two pairs of teeth, inner pair larger and about as far apart as antennal sockets; margin between inner teeth emarginate. Sides of clypeal process distinctly convergent towards apex; apical corners closer to each other than centres of antennal sockets. Scutum shiny between punctures.....***C. astarte*** Banks*

18. Clypeal process with deep triangular emargination, its apical edge almost straight in anteroventral view, rounded over medially. [Median tooth of clypeal margin broad, rectangular. Markings of body bright yellow.].....***C. dentifrons*** Cresson
– Clypeal process less deeply and more evenly emarginate; its apical edge acute medially and usually strongly curved in anteroventral view.....19

19. Median tooth of clypeal margin broad, rectangular. Body markings pale yellow to ivory.....***C. nigrescens*** F. Smith
– Median tooth of clypeal margin narrow, triangular. Body markings bright yellow.... .....***C. arelate*** Banks

Males

(Antenna with eleven flagellomeres, metasoma with seven apparent segments.)

1. Sternum 2 with median subbasal swelling.....2
– Sternum 2 flat.....6

2. Clypeus extensively black, especially laterally.....3
– Clypeus yellow except apical margin.....4

3. Tegula with coarsely punctate summit. Metanotum yellow (yellow spot evanescent in some specimens). Tergum 1 usually marked with ferruginous; tergum 3 with complete yellow apical fascia.....***C. crucis*** Viereck & Cockerell*
– Tegula with impunctate summit. Metanotum black. Tergum 1 black, without ferruginous markings; tergum 3 with pair of broadly separated yellow lateral spots... .....***C. kennicottii*** Cresson*

4. Tegula moderately and evenly convex, with indistinct punctures. Scutellum black. Propodeal enclosure smooth with weakly impressed median groove..... .....***C. nitidoides*** Ferguson
– Tegula distinctly humped (Fig.7, 8) and coarsely punctured. Scutellum with pair of yellow lateral spots (spots evanescent in some specimens). Propodeal enclosure with distinct transverse ridges.....5

5. Metanotum with coarse, contiguous punctures, with no interspaces except along posterior margin. Tegula moderately convex (Fig. 7), convexity subequal to greatest

diameter of flagellomere III. Apical fascia of tergum 2 with slightly convex or straight anterior margin. Erect setae of sterna 3–6 shorter (length < 1 MOD)..... .....***C. echo*** Mickel*

– Metanotum with extensive shiny interspaces between small punctures. Tegula extremely convex (Fig. 8), convexity subequal to 1.5x greatest diameter of flagellomere III. Apical fascia of tergum 2 emarginate anteriorly. Erect setae of sterna 3–6 long (length > 1 MOD).....***C. finitima*** Cresson*

6. Setal brushes of clypeal margin very broad, separated by distinctly less than their own width. Scutellum with yellow band. Tergum 2 black, lacking apical fascia; terga 1 and 3 with broad apical fasciae; fasciae narrow on terga 4 and 5..... .....***C. insolita*** Cresson*

– Setal brushes of clypeal margin separated by at least their own width, not extending onto median lobe. Scutellum black or with pair of yellow spots, exceptionally with yellow band. Tergum 2 with well developed apical fascia, other terga variable.....7

7. Apical fascia of tergum 2 broader than those of following terga.....8

– Apical fasciae of terga 2–4 subequal.....14

8. Flagellomere XI without outstanding setulae on posterior surface.....9

– Flagellomere XI with a few outstanding setulae on posterior surface (e.g., Fig. 5)..... 12

9. Scape and clypeus black, the latter in some cases with small ivory spot(s). Pale markings of body ivory.....***C. fumipennis*** Say*

– Anterior surface of scape yellow. Clypeus yellow except apical margin. Pale markings of body yellow.....10

10. Tergum 7 with pair of basolateral setal tufts. Sterna 3–5 with conspicuous, dense erect hair. Hind basitarsus somewhat swollen apically and slightly curved outward (Fig. 10). Flagellomere XI conspicuously curved (Fig. 6).....***C. bicornuta*** Guérin*

– Tergum 7 with scattered setae laterally. Sterna 3–5 with moderately dense, inclined hair. Hind basitarsus simple. Flagellomere XI nearly straight.....11

11. Flagellomeres (VIII–)IX–XI with bare posterior patches (devoid of microtrichia). Yellow area of median clypeal lobe more rounded ventrally. Metanotum black..... .....***C. rufopicta*** F. Smith

– Apical flagellomeres without bare posterior patches, evenly covered with microtrichia. Yellow area of median clypeal lobe more or less triangular and pointed ventrally. Metanotum with yellow band.....***C. compacta*** Cresson*

12. Clypeus conspicuously flattened (Fig. 2). [Flagellomere IX with low posterior swelling, visible as slight convexity in profile; as in Fig. 5.].....***C. halone*** Banks

– Clypeus with the usual slight convexity (Fig. 3).....13

13. Flagellomere IX without posterior swelling (straight in profile but with the usual bare patch). Lower surface of flagellum orange.....***C. clypeata*** Dahlbom

– Flagellomere IX with low posterior swelling visible in profile (Fig. 5). At least median portion of flagellum black ventrally..... .....***C. atramontensis*** Banks and ***C. prominens*** Banks*

Note: Males of *C. atramontensis* and *C. prominens* cannot be separated based on morphological characters. While the former is one of the most common species of the genus in Ontario (distribution: southern Ontario north to Killarney Provincial

Park) the latter is known only from a few specimens collected around 1900 in the Ottawa area (Buck 2004).

14. Median clypeal lobe with lateral teeth only, median tooth absent. Posterior fringe of erect setulae present on whole length of flagellomeres XI and X, fairly dense at base of flagellomere XI. Propodeal enclosure smooth except for weakly impressed median groove.....***C. astarte*** Banks*
– Median clypeal lobe with median tooth (indistinct in atypical specimens). Posterior fringe of erect setulae interrupted or sparse near base of flagellomere XI, setulae on flagellomere X restricted to apical half or less. Propodeal enclosure with more or less distinct longitudinal ridges.....15
15. Clypeus flattened, with welt-like transverse swelling above margin of median lobe. Width of median clypeal lobe > 1/3 clypeal width, with distinct emarginations between teeth.....***C. deserta*** Say
– Clypeus convex, without transverse swelling above margin of median clypeal lobe. Width of median clypeal lobe < 1/3 clypeal width; emarginations between teeth indistinct.....16
16. Clypeus more strongly convex (Fig. 4). [Body markings yellow] (Ontario, one record only).....***C. occipitomaculata*** Packard*
– Clypeus weakly convex (as in Fig. 3). Mostly commonly collected species.....17
17. Body markings ivory to pale yellow. [Apical flagellomeres as in *C. arelate*] (see below).....***C. nigrescens*** F. Smith
– Body markings bright yellow or slightly paler.....18
18. Flagellomeres (V–)VI–XI each with bare patch (devoid of microtrichia) posteriorly (patches becoming smaller on more basal flagellomeres).....***C. dentifrons*** Cresson
– Only flagellomeres (IX–)X–XI with bare patch ventrally (small on flagellomere IX if present).....***C. arelate*** Banks

Note: This character requires careful examination under critical lighting.

Colletidae

***Hylaeus* (*Spatulariella*) *hyalinatus* F. Smith, 1843**

CANADA, Ontario: Halton Reg., Oakville, 16 Mile Creek nr. Hwy 407, ♂, ♀, 21 August 2004, ♂, 25 June 2005, M. Buck. **Essex Co.**, ♂, W of Harrow, 28 June 1993, edge of farmer's field, pheromone trap, J. Doherty.

Newly recorded from Canada. This Palaearctic species was first recorded from the Nearctic region by Ascher (2001) based on material collected in New York in 1997 and later. All New York state records are from the Ithaca area (Tompkins Co.) and the New York City area (Bronx Co., New York Co., Westchester Co.) (Ascher et al. 2006). The earliest specimen from Ontario was collected in 1993 (see above), and now represents the oldest known record from North America. *Hylaeus hyalinatus* is distinguished easily from other northeastern *Hylaeus* by the well-developed omaulus and the protruding spatulate process of male sternum 8. The male terminalia and facial markings were illustrated by Ascher (2001). This species nests in a great variety of cavities in and above the ground, including abandoned solitary wasp or bee nests, hollow twigs, and borings in wood, etc. (Ascher l.c.).

Megachilidae

***Chelostoma* (*Chelostoma*) *campanularum* (Kirby, 1802)**

CANADA, Ontario: York Reg., ♂, Etobicoke, 29 June 1997, backyard, C. S. Onodera; 2♂, 10♀, Toronto, Humber River nr. old mill, 11 July 1999, T. Romankova (ROME). **Wellington Co.**, 3♀, Guelph, 22 July 2004, on *Campanula*, S. M. Paiero; ♀, Guelph, Wellington St. & Fife Rd., 4 September 2004, at roots of uprooted tree, M. Buck. **Halton Reg.**, ♂, Oakville, 21 July 1976, W. A. Attwater. **Welland Co.**, ♀, Welland, 27 June 1977, R. G. Bennett.

Newly recorded from Canada. This is another Palaearctic species that has apparently been introduced accidentally to North America. Previously, the species was known only from New York, where it was first collected in 1973 (Eickwort 1980). *Chelostoma campanularum* nests in borings in wood or hollow twigs, and was probably introduced with shipments of wood (e.g., wooden pallets) containing nests. The species is oligolectic on *Campanula* (Eickwort l.c.).

***Chelostoma* (*Gyrodromella*) *rapunculi* (Lepeletier, 1841)**

CANADA, Ontario: Halton Reg., ♂, ♀, Oakville, 16 Mile Creek nr. Hwy 407, 25 June 2005, visiting flowers of *Echium vulgare* L., M. Buck.

As the previous species, *Ch. rapunculi* is native to the Palaearctic region, and is recorded for the first time from Canada. It was first discovered in the Nearctic region by Eickwort (1980) based on specimens collected in New York as early as 1962. The biology is similar to *Ch. campanularum*, with females being oligolectic on *Campanula*, though our specimens were visiting flowers of viper's bugloss (*Echium vulgare*). The differences between the two introduced and the single native eastern Nearctic species of *Chelostoma* are summarized in the key below.

Key to the eastern Nearctic species of *Chelostoma* Latreille

1. Female (ten flagellomeres; metasomal sterna with scopa).....2
– Male (eleven flagellomeres; scopa absent).....4
2. Terga 1–4 with apical fasciae of white appressed pubescence. Body length 8–11 mm.....***Ch. rapunculi*** (Lepeletier)
– Terga 1–4 without fasciae of appressed pubescence. Body length 5–8 mm.....3
3. Length of mandible approximately 2/3 eye height (Eickwort 1980: Fig. 3). Flagellomeres VIII and IX at least as long as wide. Setae of mid basitarsus simple.....***Ch. philadelphi*** Robertson
– Length of mandible approximately half eye height (Eickwort 1980: Fig. 2). Flagellomeres VIII and IX wider than long. Setae of mid basitarsus conspicuously plumose.....***Ch. campanularum*** (Kirby)
4. Apical tergum trilobate, median lobe below paired lateral lobes; lobes truncate apically (Eickwort 1980: Fig. 6). Clypeus truncate apically. Sternum 2 with prominent, nearly semicircular protuberance (posterior view). Body length 8–11 mm.....***Ch. rapunculi*** (Lepeletier)

– Apical tergum with paired lobes only, lacking median lobe. Sternum 2 with low, transverse, welt-like swelling. Body length 5–8 mm.....5

5. Apical tergum quadridentate, lateral pair of teeth about half the size of paramedian pair (Eickwort 1980: Fig. 4). Flagellomere II longer than wide and longer than flagellomere I.....***Ch. philadelphi*** Robertson

– Apical tergum bidentate, only paramedian pair of teeth present, elongate (Eickwort 1980: Fig. 5). Flagellomere II wider than long, at most as long as flagellomere I..... .....***Ch. campanularum*** (Kirby)

***Hoplitis* (*Hoplitis*) *anthocopoides* (Schenk, 1853)**

CANADA, Ontario: Peel Reg., ♀, Forks of the Credit, gravel pit NW of Provincial Park, 43°49'24"N, 80°0'57"W, 5 August 2002, white pan traps, M. Buck. **Wellington Co.**, ♂, Rockwood, Valley Rd., 43°46'56"N, 80°8'28"W, 21 July 2004, on rock and mortar walls of ruin of house, M. Buck; 6♂, 4♀, Guelph, Niska Rd., Guelph Bird Sanctuary, 11 June 2005, abandoned gravel pit, M. Buck; 3♂, 2♀, Guelph, Wellington & Fife Rds., 12 June 2005, abandoned lot, M. Buck; 3♂, ♀, same locality, reared from mortar nests on rocks collected on 1 June 2005 (emergence dates in lab: ♂, 14 June, ♂, 15 June, ♂, ♀, 30 June 2005), M. Buck. **Halton Reg.**, Milton, Woodland Trails camp, 6th Line Nassagaweya, 43°32'51"N, 79°59'35"W, ♂, 27 June 2005, ♂, 2♀, 8 July 2005, S. M. Paiero.

This species is also native to Europe and is newly recorded from Canada. It was known previously from New York, where it was first collected in 1969 (Eickwort 1970). According to S. Droege (in litt.) the species now also occurs in West Virginia (Hampshire Co., 2004). The biology of *H. anthocopoides* was studied thoroughly by Eickwort (1973). Unlike native *Hoplitis* (which belong to different subgenera) this species is a true mason bee, i.e. it builds "mortar and pebble" nests. The nests are constructed on exposed areas of rocks (large or small), rubble, stone walls, etc. The females are oligolectic on viper's bugloss, an introduced European weed that is widespread in disturbed areas with poor soil. This species can be separated from other species of *Hoplitis* using Mitchell (1962) in conjunction with the supplementary couplets provided by Eickwort (1970).

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References

Ascher, J. S. 2001. *Hylaeus hyalinatus* Smith, a European bee new to North America, with notes on other adventive bees. Proceedings of the Entomological Society of Washington 103: 184–190.

Ascher, J. S., P. Gambino, and S. Droege. 2006. Adventive *Hylaeus* (*Spatulariella*) Popov in the New World (Hymenoptera: Apoidea: Colletidae). Proceedings of the Entomological Society of Washington 108: 237–239.

Bitsch, J., Y. Barbier, S. F. Gayubo, K. Schmidt, and M. Ohl. 1997. Hyménoptères Sphecidae d'Europe occidentale, Vol. 2. Faune de France. France et régions limitrophes 82, 429 pp., Fédération Française des Sociétés de Sciences Naturelles, Paris.

Blüthgen, P. 1961. Die Faltenwespen Mitteleuropas (Hymenoptera, Diploptera). Abhandlungen der Deutschen Akademie der Wissenschaften zu Berlin, Klasse für Chemie, Geologie und Biologie 1961 (2): 251 pp.

Bohart, R. M. and L. S. Kimsey. 1979. A key to the species of *Ectemnius* in America north of Mexico with notes and description of a new species (Hymenoptera: Sphecidae). Proceedings of the Entomological Society of Washington 81: 486–498.

Bohart, R. M. and A. S. Menke. 1963. A reclassification of the Sphecinae with a revision of the Nearctic species of the tribes Sceliphronini and Sphecini (Hymenoptera, Sphecidae). University of California Publications in Entomology 30: 91–181.

Bohart, R. M. and N. J. Smith. 1995. Contributions to the knowledge of the genus *Spilomena* Shuckard in America north of Mexico (Hymenoptera, Sphecidae, Pemphredoninae). Journal of the Kansas Entomological Society 67 (1994): 318–330.

Buck, M. 2004. An annotated checklist of the spheciform wasps of Ontario (Hymenoptera: Ampulicidae, Sphecidae and Crabronidae). Journal of the Entomological Society of Ontario 134 (2003): 19–84.

Buck, M. 2005. Two introduced spider wasps (Hymenoptera: Pompilidae) new to Canada, with notes on nesting habits and the incidence of introductions. The Canadian Entomologist 137: 278–282.

Buck, M., S. A. Marshall, and D. Cheung in prep. Taxonomy and distribution of eastern Canadian Vespidae (Hymenoptera), including keys to northeastern Nearctic species. The Biological Survey of Canada Journal of Arthropod Identification [a web publication series, see: www.biology.ualberta.ca/bsc/bschome.htm]

Dollfuss, H. 1986. Eine Revision der Gattung *Spilomena* Shuckard der westlichen und zentralen paläarktischen Region (Hymenoptera, Sphecidae). Annalen des Naturhistorischen Museums in Wien 88/89B: 481–510.

Eaton, E. R. 2005. *Isodontia elegans* [comment posted 5 July 2005]. www.bugguide.net/node/view/22899 (last accessed 19 September 2005).

Eickwort, G. C. 1970. *Hoplitis anthocopoides*, a European mason bee established in New York State (Hymenoptera: Megachilidae). Psyche 77: 190–201.

Eickwort, G. C. 1973. Biology of the European Mason Bee, *Hoplitis anthocopoides* (Hymenoptera: Megachilidae), in New York state. Search Agriculture 3(2): 1–30.

Eickwort, G. C. 1980. Two European species of *Chelostoma* established in New York state (Hymenoptera: Megachilidae). Psyche 87: 315–323.

Evans, H. E. 1961. A preliminary review of the Nearctic species of Sierolomorphidae (Hymenoptera). Breviora 140: 1–12.

Gusenleitner, J. 1995. Bestimmungstabellen mittel- und südeuropäischer Eumeniden (Vespoidea, Hymenoptera) Teil 4: Die Gattung *Ancistrocerus* Wesmael, 1836 mit einem Nachtrag zum Teil 1: Die Gattung *Leptochilus* Saussure. Linzer Biologische Beiträge 27: 753–775.

Harrington, W. H. 1902. Fauna Ottawaensis. Hymenoptera – Superfamily II. – Sphegoidea. The Ottawa Naturalist 15: 215–224.

Krombein, K. V. 1979. Sphecoidea. pp. 1573–1740, *In* Krombein, K. V., P. D. Hurd, D. R. Smith, and B. D. Burks (eds): Catalog of Hymenoptera in America north of Mexico. Vol. 2: Apocrita (Aculeata). Smithsonian Institution Press, Washington.

Lomholdt, O. 1975. The Sphecidae (Hymenoptera) of Fennoscandia and Denmark. Fauna Entomologica Scandinavica 4(1): 1–224. Scandinavian Science Press, Klampenborg.

Marlin, B. 2005. Grass-carrying wasp – *Isodontia elegans* [image posted 3 July 2005]. www.bugguide.net/node/view/22899 (last accessed 19 September 2005).

Marshall, S. A., S. M. Paiero, and M. Buck. 2005. Buprestid sampling at nests of *Cerceris fumipennis* (Hymenoptera, Crabronidae) in southern Ontario, with new Canadian records of Buprestidae (Coleoptera). The Canadian Entomologist 137: 416–419.

Mitchell, T. B. 1962. Bees of the eastern United States Volume 2. North Carolina Agriculture Experimental Station Technical Bulletin 152. 557 pp.

Paiero, S. M. and M. Buck. 2004. First Canadian records of the giant resin bee, *Megachile sculpturalis* Smith, and other introduced and native Megachilidae and Andrenidae (Apoidea) from Ontario. Journal of the Entomological Society of Ontario 134 (2003): 141–143.

Pulawski, W. J. 1988. Revision of North American *Tachysphex* wasps including Central American and Caribbean species (Hymenoptera: Sphecidae). Memoirs of the California Academy of Sciences 10: vi + 211 pp.

Pulawski, W. J. 2005. Catalog of Sphecidae sensu lato (= Apoidea excluding Apidae). http://www.calacademy.org/research/entomology/Entomology_Resources/Hymenoptera/sphecidae/Genera_and_species_PDF/introduction.htm (last accessed 26 September 2005).

Romankova, T. 2004. Ontario nest-building bees of the Tribe Anthidiini (Hymenoptera, Megachilidae). Journal of the Entomological Society of Ontario 134 (2003): 85–89.

Scullen, H. A. 1965. Review of the genus *Cerceris* in America north of Mexico (Hymenoptera: Sphecidae). Proceedings of the United States National Museum 116: 333–548.

Smith, I. P. 1991. *Anthidium manicatum* (Hymenoptera: Megachilidae), an interesting new Canadian record. Proceedings of the Entomological Society of Ontario 122: 105–108.

Vikberg, V. 2000. A re-evaluation of five European species of *Spilomena* with a key to European species and relevance to the fauna of North Europe, especially Finland (Hymenoptera: Pemphredonidae). Entomologica Fennica 10: 35–55.

Walker, E. M. 1913. Insects and their allies. pp. 295–403 *In* J.H. Faull (ed.) The natural history of the Toronto region Ontario, Canada. Canadian Institute, Toronto. 419 pp.

STATUS OF RESISTANCE TO INSECTICIDES IN POPULATIONS OF THE ORIENTAL FRUIT MOTH *GRAPHOLITA MOLESTA* (BUSCK) (LEPIDOPTERA: TORTRICIDAE) IN SOUTHERN ONTARIO

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Abstract

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Populations of Oriental fruit moth *Grapholita molesta* (Busck) (Lepidoptera: Tortricidae) were assessed for levels of resistance to organophosphorus (OP) and pyrethroid insecticides approximately 10 years after initial assays identified the resistance, and 6-8 years after a resistance management strategy was introduced for use in peach production systems. Resistance to OP insecticides was detected at all three locations tested (Niagara, Norfolk, and Essex). Resistance frequencies had increased at one site (Jordan Station Experimental Farm) that had been monitored closely in 1999; however, frequencies at that site did not increase over the three years reported here. Results also indicated that pyrethroid resistance had declined in the Niagara area, occurred at low levels in the Norfolk area, and was not found in the Essex area. Mechanisms and cross resistances between OP and carbamate insecticides appeared similar to those described in earlier studies. Resistance was associated with elevated general esterase activity and the presence of an acetylcholinesterase which was less sensitive to inhibition than in susceptible populations. Resistance to azinphosmethyl and phosmet was expressed at low levels but high levels of resistance was expressed to the methyl carbamates, carbaryl, or carbofuran. Chlorpyrifos was equally toxic to both susceptible and resistant populations. Resistant populations were more susceptible to acephate. All of these characteristics were similar to the resistance described in previous reports. Chlorpyrifos, which is scheduled to be deregistered in 2006, may be replaced by the ecdysone agonist methoxyfenozide or the neonicotinoid acetamiprid. The data indicated low levels of resistance (1.7 fold at the LC_{50}) for methoxyfenozide associated with OP resistance, but control of the first generation was achieved in both small plot and program trials. Later applications were less effective. Acetamiprid was generally effective throughout the season and was equally toxic to both OP resistant and susceptible populations. In field trials over two seasons, neither of these products was associated with outbreaks of phytophagous mites. However,

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the potential fit of these products into IPM programs for peach will need further assessment.

Introduction

An integrated pest management (IPM) program for peach, introduced to growers in the mid 1970's, was the first widely used IPM program in Ontario. The program relied on the use of pheromone trap catch data to time applications of the organophosphorus insecticides azinphosmethyl and phosmet to control the Oriental fruit moth (OMF), *Grapholita molesta* (Busck) (Lepidoptera: Tortricidae) (Phillips 1973). This program remained effective for approximately 20 years but resistance to these insecticides resulted in up to 45% fruit infestations in 1993 and 1994 (Pree et al. 1998). This was the first documented occurrence of resistance to pesticides in *G. molesta* worldwide. Tests with neonate larvae (the targeted life stage in the field) indicated cross-resistance to most OP insecticides, except acephate and chlorpyrifos. Acephate was more toxic to resistant larvae than to susceptible larvae, and chlorpyrifos was equitoxic to both populations. Resistance was highest (>100 fold) to methyl carbamates, carbaryl, and carbofuran. Cross-resistance to pyrethroids was not observed. Based on these observations and additional small plot tests, growers switched to programs of repeated applications of pyrethroids. Concerns were expressed (Pree et al. 1998) that a program of repeated pyrethroid use might accelerate the development of further resistance. Therefore, an interim resistance management strategy was implemented which consisted of 1-2 applications of chlorpyrifos for the first annual generation, followed by pyrethroids for later generations. From 1996-1999, monitoring of resistance changes in commercial orchards using this program showed that resistance to OP insecticides declined from about 50% to 12%, while pyrethroid resistance was approximately 16% (Kanga et al. 2003). While this program successfully reduced the risk that resistance to pyrethroids might become common, registration of chlorpyrifos was granted only on a temporary and annual basis, and deregistration is scheduled for 2006 (Pest Management Regulatory Agency 2003).

We report on the current status of resistance to organophosphorus (OP) and pyrethroid insecticides in both apple and peach plantings in southern Ontario, provide an update on the mechanisms of OP resistance, and compare both of these findings to previous studies. Further, with the impending removal of chlorpyrifos, we also report on the effectiveness of potential alternative materials and how they might fit into both Integrated Pest Management and resistance management programs for Oriental Fruit Moth populations in tree fruit.

Methods

Oriental fruit moth populations

The population of Oriental fruit moth used as the standard susceptible population was the same colony used in earlier studies (Pree et al. 1998; Kanga et al. 1999) and unless otherwise indicated was maintained on small green apples as described by Pree (1985).

This colony has been maintained unselected with few infusions of field collected insects (none since 1985) for approximately 50 years.

The standard resistant population in these tests was collected from a mixed apple/peach/pear planting near Beamsville, ON in 2002. Initial tests using a standard field resistance monitoring procedure (Kanga et al. 1999) indicated that approximately 75% of the population was resistant to OP and carbamate insecticides. The colony was established on apple from 200-300 larvae. Larvae of this population were selected in each generation with carbaryl at 150 mg/L using a Potter spray tower using procedures described by Pree (1979). Newly hatched larvae were held in Petri dishes on ice and sprayed with 5 ml of a 150 mg/L solution of carbaryl in analytical grade acetone. Sprayed larvae were transferred to apples in a standard rearing container (Pree 1985). Laboratory bioassays with neonate larvae were conducted with the 9^{th}-15^{th} laboratory selected generations.

For tests with methoxyfenozide, which is more active when ingested, we developed subcolonies of each population adapted to an artificial diet. The diet was modified from that of Yokoyama et al. (1987) and initially resulted in some larvae mortality (previously adapted to green apples), but this decreased after 3-4 generations on the diet. Larvae were used for tests after at least 6 generations on the diet. Three or four Oriental fruit moth neonate larvae were placed in plastic cups (souffles) (P100, 25 ml capacity, SOLO Cup Company, Urbana, IL) each containing about 10 ml of diet. Pupae were removed after 3-4 weeks and held in rearing jars (Pree 1985) for adult emergence.

Preparation of artificial diet

The diet consisted of: 3.0 g methyl-*p*-hydroxybenzoate, 1.8 g sorbic acid, 7.0 g *L*-ascorbic acid, 10.5 g fructose, 13.0 g Vanderzant vitamin mix, 17.5 g α-protein (soybean protein), 35.0 g wheat germ, 70.0 g Brewers yeast, 350.0 g ground pinto beans (BioServ, Frenchtown, NJ), and 1500 ml distilled water.

Unless indicated, all ingredients were from ICN Biomedical (Aurora, OH). Dry ingredients were blended for approximately 30 seconds with 1500 ml distilled water until a smooth consistency was obtained. A 1 L media bottle containing 500 ml distilled water and 16 g of agar was autoclaved until the mixture boiled, and the warm agar was thoroughly mixed with the aqueous nutrient mixture. Warm diet mix was transferred to plastic squeeze bottles and dispensed into individual cups. Cups (25 ml capacity) were filled to an approximate depth of 1.5 cm, allowed to cool at room temperature, capped when condensation had disappeared, and stored at room temperature until needed. The quantities listed here provided approximately 400 individual cups of diet.

BIOASSAYS

Determination of resistance frequencies in field population

Resistance frequencies for OP and pyrethroid insecticides in the various orchard populations and locations were monitored as described by Kanga et al. (1999; 2003). Adult males captured in pheromone-baited traps were brought to the laboratory and fed overnight with a 10% sucrose solution. They were then exposed to insecticides in glass vials as described by Kanga and Plapp (1995). For tests with the Niagara populations, one or two moths were placed in each vial and held for 24 hours in a cabinet at 22 ± 2°C, 60% relative humidity (RH), and 16:8 Light:Dark (L:D) cycle. Assays with populations from Norfolk

and Essex were conducted in the test areas on a laboratory bench where temperatures were similar but RH values were lower (about 40%). Adults unable to fly when tossed into the air were considered dead (Kanga et al. 1999). The diagnostic concentrations used in all bioassays were those used by Kanga et al. (2003) but were verified as diagnostic prior to use here. Concentrations used were 0.1 µg/vial for carbofuran (which indicates both OP and carbamate resistance and used because the higher level of resistance results in a better separation of resistant and susceptible populations) (Kanga et al. 2003) and 2.5 µg /vial for cypermethrin (as diagnostic of pyrethroid resistance). Both of these concentrations killed all of a susceptible population. The carbofuran treatment did not affect any of an OP resistant population whereas in tests by Kanga et al. (1999), cypermethrin at 2.5 µg/ vial killed approximately 25% of a pyrethroid resistant population. We did not have a pyrethroid resistant population for comparison. There were 100-250 male moths tested for each compound per generation per site reported. Data from 3-4 days trapping were combined and mean survival rate over the generation trapped is presented.

Contact toxicity tests

Tests with contact insecticides on neonate larvae were similar to those described by Pree et al. (1998). Insecticides, technical or analytical grade, obtained either from the manufacturers or from Chem Services (West Chester, PA), were applied to first instar larvae with a Potter spray tower in 5 ml of analytical grade acetone. After treatment, larvae were held in plastic Petri dishes (Falcon 1006, Becton Dickinson, Lincoln Park, NJ) for 2 hours at 22 ± 2°C and 60% RH. Larvae that were unable to crawl when prodded were considered dead. Mortality data from six concentrations of each insecticide with 10 replications of 10 larvae were used to plot regression lines of concentration vs. mortality. Data were subjected to probit analysis (POLO-PC, Le Ora Software, Berkeley, CA). Resistance ratios were considered significantly different if the 95% confidence limits at the LC_{50} did not overlap.

Insecticide-diet mixtures

For tests with artificial diets, measured amounts of commercial formulations of the test chemicals, methoxyfenozide (Intrepid 240F, DowAgrosciences Canada Inc, Calgary, AB) or acetamiprid (Assail 70WP, Dupont Canada Inc, Mississauga, ON) were diluted in 10 ml of distilled water and added to 390 ml of freshly prepared diet to provide the desired final concentration expressed as mg/l active ingredient (ai). The diet and test chemical were mixed thoroughly in a Waring blender and distributed approximately evenly into 50 SOLO cups (P100, SOLO Cup Company). Two neonate larvae were added to each cup and held in a cabinet at 22 ± 2°C, 60% RH, and a 16:8 L:D regime. Five concentrations plus a water treated control were used for each chemical and each population with 10 replicates of 5 cups each. Tests were set up over at least 2 days with fresh insecticide, diet preparations and newly hatched larvae each day. Mortality was assessed after 4 and 6 weeks when cups were examined for pupae. Cups containing no pupae were rated as negative or dead. Cups which held one or 2 pupae were classed as positive (alive). Data were expressed as the proportion of cups with dead larvae based on 10 replicates of 10 cups each (percent mortality). Mortality in controls (i.e. control cups which produced no pupae) was 4-6%. Concentration:mortality data were analyzed by probit analysis as described for contact toxicity tests above. Differences between responses were considered significantly different

if the 95% confidence limits at the LC_{50} did not overlap.

BIOCHEMICAL ASSAYS

General esterase

Esterase activity in the susceptible and OP-resistant populations was measured using a procedure adapted from Herath et al. (1987) that used α-naphthyl acetate as a substrate. The reaction mixture consisted of 800 µl of α-naphthyl acetate (0.3 mM) in 0.1 M, pH 7.2 phosphate buffer, and 100 µl of insect homogenate. One adult abdomen/ml was homogenized in ice-cold phosphate buffer and the homogenate centrifuged at 10,000 g for 10 minutes at 4°C. The supernatant was used in assays. The reaction was run in a 1.5 ml Eppendorf tube in an Eppendorf Thermomixer at 37°C and 450 rpm. The reaction was stopped after 15 minutes with 80 µl of a solution of 100 mg of Fast Blue B salt in 50 ml of a 5% solution of sodium dodecyl sulfate. The change in absorbance at 450 nm was measured on an Ultraspec 3100 pro spectrophotometer (Biochrom Ltd, Cambridge, UK). There were 15 replications over 12 different days using 112-121 insects for each population. Protein concentrations in tissue homogenates were determined by the method of Bradford (1976). Mean esterase activities were compared using an unpaired t-test ($P<0.05$) (Sigmastat Version 2.0, SPSS Inc, Chicago, IL).

Acetylcholinesterase assays

Acetylcholinesterase (AChE) activity was measured using acetylthiocholine as a substrate (Ellman et al. 1961). Inhibition of AChE was determined using methods adapted from Moores et al. (1988) and Pree et al. (2003). For assays, moth heads were frozen at –70°C for at least 30 minutes and each head was placed into a 1.5 ml Eppendorf tube; 50 µl of 0.1 M phosphate buffer (pH 7.5) was added, and the head was ground for 10-15 seconds. This homogenate was held on ice until used. The reaction mixture was 25 µl of homogenate, 50 µl of 1 mM 5,5-dithio-bis (2-nitrobenzoic acid) (DTNB) in 0.1 M phosphate buffer (pH 7.5), and 100 µl of 0.1 M phosphate buffer containing Triton X-100 (10 g/l). This mixture was equilibrated for 2 minutes in an Eppendorf tube and the reaction started with the addition of 20 µl of the substrate (1mM acetyl thiocholine iodide). For inhibition tests, 20 µl of 10^{-4} M carbaryl in ethanol was placed in tubes prior to the addition of the reaction mixture and the ethanol evaporated. The rate of change at OD 405, was measured for the initial 10 minutes of the reaction in an Ultraspec 3100 Pro spectrophotometer. For protein determinations, one adult Oriental fruit moth head was ground in 50 µl of 0.1 M phosphate buffer with no Triton X-100 and 10 µl was used in the Bradford (1976) assay for protein with bovine serum albumin as the standard. Activity (and inhibition at 10^{-4} M carbaryl) was determined for males and females of both populations. Data were based on 12-14 replications of 96-101 individuals. Differences between means were identified by an analysis of variance and a Tukey test ($P<0.05$) (Sigmastat Version 2.0 SPSS, Chicago, IL).

FIELD TESTS OF ALTERNATIVE INSECTICIDES

Trials were conducted at the Jordan Station Experimental Farm of Agriculture and Agri-Food Canada (AAFC), Jordan, ON. For tests in small plots, treatments were replicated 4 times, assigned to 2 tree plots arranged according to a randomized complete block design. Based on pheromone trap catches of male moths in adjacent or nearby plantings,

applications were timed for egg hatch of the first or second generations of Oriental fruit moths using standard methods (Pree et al. 1983) and a phenology model (Rice et al. 1982) that used 7.2°C as a base temperature. Trees were spaced 4.6 x 5.5 m and were 3-6 years old as indicated. Insecticides were diluted to a rate comparable to 3,000 L/ha and trees sprayed to runoff with a truck-mounted sprayer (Rittenhouse Sprayers Ltd., St. Catharines, ON) equipped with a Spraying Systems handgun (Spraying Systems Co., Wheaton, IL) fitted with a D-6 orifice plate. Pressure was set at 2,000 kPa. Nine to thirteen L of spray mix was applied per plot. Plots were assessed 10-19 days post-spray when all twig and fruit damage was removed and counted. Data were analyzed using an analysis of variance and a Tukey test ($P<0.05$).

In larger scale trials, insecticides were applied to approximately 0.50 ha blocks of mature cv. Loring peach trees at the AAFC Jordan Station Experimental Farm in season-long programs. All plots were treated with superior oil (60 L/ha) as a dilute spray (20 L/1000 L water) in April for control of overwintered eggs of European red mite (*Panonychus ulmi* (Koch), Acari: Tetranychidae).

In 2003, we assessed 3 programs. The most widely used commercial program for control of Oriental fruit moth consists of 1.7 kg ai/ha chlorpyrifos (Lorsban 50W, Dow AgroSciences, Calgary, AB), for generation 1, followed by pyrethroids for generations 2 and 3 (program 1). In our tests we used 10 g ai/ha deltamethrin (Decis 5 EC, Bayer CropSciences, Calgary, AB). Program 2 was 360 g ai/ha methoxyfenozide (Intrepid 240F, Dow AgroSciences) for generation 1, followed by deltamethrin for generations 2 and 3. Program 3 was chlorpyrifos for generation 1 followed by methoxyfenozide for generations 2 and 3. Treatments were applied using a Rittenhouse GB Laser P20 sprayer (Rittenhouse Sprayers Ltd., St. Catharines, ON) set to deliver 840 L/ha and were timed using standard procedures (Pree et al. 1983) based on data from pheromone-baited traps placed in test plots or in nearby peach plantings. Insecticides were applied 30 May for generation 1, 16 July and 1 August for generation 2 and 30 August for generation 3 (and as a preharvest treatment). Infested terminals were assessed 17 June and 30 July when all of the terminals on 10% of the trees in each plot were examined for damage by larvae. At harvest, on 8 and 10 September 2003, we examined 10-12 of the ripest fruit on each tree for Oriental fruit moth damage. Further, 20% of these fruit were cut apart and checked for damage not visible from surface assessments. Data from twig damage and fruit assessments did not fit a normal distribution and attempts to transform data were unsuccessful (based on Kolmogorov-Smirnov test with Lilliefors' correction), so were analyzed using a Kruskal-Wallis test (Sigmastat Version 2.0).

Mite populations were assessed 25 August when 3 replicate samples of 100 leaves were collected from each plot. Leaves were examined for numbers of European red mite *Panonychus ulmi* (Koch) (Acari:Tetranychidae), peach silver mite *Aculus cornutus* Banks (Acari: Eriophyidae), and for predaceous mites (Acari: Phytoseidae). For each sample, 20 leaves were examined under a binocular microscope and an additional 80 leaves brushed with a Henderson-McBurnie mite brushing machine (Henderson and McBurnie 1943). Peach silver mite infestations were assessed on 20 leaves/sample. Infestations were rated on a scale of 0-5: 0 = 0 mites/leaf; 1 = 1-10 mites/leaf; 2 = 11-25 mites/leaf; 3 = 26-50 mites/leaf; 4 = 51-100 mites/leaf; 5 = 101+ mites/leaf. After testing for fit in a normal distribution, data were analyzed by analysis of variance with differences between treatment

means identified using a Tukey test ($P<0.05$).

In 2004, 4 programs were assessed: Program 1-chlorpyrifos for generation 1 followed by deltamethrin for generations 2 and 3; Program 2-methoxyfenozide for generation 1, with deltamethrin for generations 2 and 3; Program 3-acetamiprid for generation 1, methoxyfenozide for generations 2 and 3; and Program 4-methoxyfenozide for generation 1, acetamiprid for generations 2 and 3. Rates used were as in 2003 with acetamiprid (Assail 70WP) applied at 168 g ai/ha. Treatments were timed as described by Pree et al. (1983) with applications on 21 May for generation 1, 9 July for generation 2, and 6 and 24 August (preharvest) for generation 3. On 8 June and 28 July, infested terminals were counted and removed on 10% of the trees, selected randomly, in each block. At harvest, 27 and 30 August, we examined 10-12 of the ripest fruit on each tree for damage by Oriental fruit moth larvae. As in 2003, we cut apart 20% of these fruit and checked for damage not visible from surface assessments. Data from assessment of damaged twigs by generation 2 larvae did not fit a normal distribution until transformed (log x +1). Data were analyzed by an analysis of variance and differences between means were separated by a Tukey test ($P<0.05$). Mites were sampled August 25 as described above for 2003. Data were analyzed as described for 2003.

Results

Status of resistance in field populations

The occurrence of resistance to organophosphorus (OP) and carbamate insecticides at the Jordan Station site ranged from 31% in generation 1 in 2004 to 75% in generation 2 in 2003 (Table 1). The diagnostic concentrations used for tests allowed survival of resistant insects only. Over the three seasons at the Jordan Station site, resistance rates were similar in generation 1 (from 31-39%), but were generally higher than reported for the same location in 1999 by Kanga et al. (2003) who found a decline to <20% resistance for OP insecticides. Resistance to OP insecticides was usually highest at the end of each season in generation 3. Resistance to OP insecticides in the populations from the Niagara peninsula were always lowest in the first or overwintered generation and lower than in the third generation of the previous year at the Jordan site where observations were made over 3 years. The Grimsby site, largely planted with apples (no peach) and the Beamsville site, a mixture of peach, apple, and pear, showed similar patterns of increased frequencies of OP resistance over the season. However, OP resistance did not continue to increase over the 3 years of sampling at the Jordan Station site, nor did resistance levels in generation 3.

Control programs for Oriental fruit moth on peach were chlorpyrifos for the first generation followed by up to four applications of a pyrethroid (cypermethrin, deltamethrin, or, lambda cyhalothrin) over the rest of the season. Programs on apple were variable but most included at least one application of azinphosmethyl or phosmet. Resistance to pyrethroids did not increase over the three seasons sampled at the Jordan site and was generally lower than OP resistance at all locations tested in Niagara. Resistance to pyrethroids was similar or lower than reported in previous studies by Kanga et al. (2003).

Sites sampled in Norfolk (Table 2) were all apple and all showed the occurrence of resistance to OP insecticides at frequencies up to 54%. The percent identified as resistant

TABLE 1. Occurrence of resistance in Oriental fruit moth populations with organophosphorus (OP) and pyrethroid insecticides in the Niagara peninsula, ON, 2002-2004. The survival rate is based on 100-120 adult males/ generation for each insecticide. OP resistance determined with carbofuran, pyrethroid resistance with cypermethrin. Diagnostic concentrations used killed all susceptible mortality data indicate percent resistant moths.

	Survival Rate (%) ± SE					
	OP Generation			Pyrethroid Generation		
Site	1	2	3	1	2	3
2002						
Jordan Station	39.0 ± 17.3	53.0 ± 6.0	59.9 ± 7.7	0	1.0 ± 2.0	1.0 ± 1.9
Grimsby	29.3 ± 2.9	35.8 ± 13.2	71.3 ± 4.7	0.9 ± 1.9	2.8 ± 3.5	0
Beamsville	72.2 ± 7.5	74.3 ± 11.6	83.9 ± 4.6	0.8 ± 1.7	3.0 ± 3.8	8.8 ± 6.0
2003						
Jordan Station	34.8 ± 14.0	75.4 ± 5.2	n.a.	0	1.2 ± 13.9	n.a.
2004						
Jordan Station	31.0 ± 6.8	38.0 ± 6.9	53.0 ± 12.8	0	1.0 ± 2.0	0
Vineland	45.0 ± 19.7	61.0 ± 22.0	58.0 ± 10.6	1.3 ± 2.3	1.7 ± 2.9	0

declined over the 3 seasons of the test at the Simcoe site but this was the only location sampled each season and initial samples (2001) were from generation 3 when resistance was generally higher than in generation 1 (Kanga et al. 2003). Pyrethroid resistance was detected at most of the sites.

In Essex county (Table 2), samples were largely from peach plantings and both the Oxley and Varner populations showed OP resistance but not pyrethroid resistance. Whether resistance to pyrethroids declined (despite up to 4 applications/season) and OP resistance increased relative to levels indicated in earlier reports (Kanga et al. 2003) or whether these results are an expression of fluctuations in resistance frequencies and do not necessarily represent trends, is not clear. Most of the sites trapped in these studies had not been previously tested but the Jordan Station site had been extensively tested by Kanga et al. (2003). It seems unlikely that changes in bioassay techniques were responsible for these observed changes because concentration: response regressions were redeveloped for these tests and produced results similar to those used in earlier assays by Kanga et al. (2003). Diagnostic concentrations were the same as in their earlier report. These data may support the argument of Tabashnik et al. (2000) that the frequency of resistance does not necessarily increase each season despite considerable selection pressures. They reported that Bt resistance frequencies in pink bollworm *Pectinophora gossypiella* (Saunders) (Lepidoptera: Gelechiidae) did not increase as expected over three seasons (1997-1999)

TABLE 2. Occurrence of resistance to organophosphorus (OP) and pyrethroid insecticides in Oriental fruit moth populations from Norfolk and Essex counties, ON, 2001-2003. Survival rate was based on the responses of 100-250 males.

Site	Generation	Survival Rate (%) ± SE OP	Pyrethroid
Norfolk County			
2001			
Walsh	3	49.1 ± 4.9	3.9 ± 2.7
Simcoe	3	29.1 ± 9.5	1.1 ± 1.3
Vittoria	3	29.8 ± 5.0	2.6 ± 3.3
2002			
Walsh	1	54.0 ± 16.0	5.0 ± 3.4
Simcoe	1	20.0 ± 9.9	2.4 ± 4.8
Vittoria	1	36.3 ± 20.1	7.1 ± 4.7
2003			
Renton	1	24.1 ± 2.8	0
Simcoe	1	13.7 ± 6.3	0
Essex County			
2003			
Oxley	1	60.0 ± 10.9	0
Varner	1	41.9 ± 14.7	0

despite high levels of selection from Bt cotton.

Laboratory tests

Laboratory bioassays of neonate larvae with the population collected from Beamsville and selected in the laboratory (Table 3) indicated that the characteristics of the resistance levels expressed were similar to those reported for populations collected in 1994 (Pree et al. 1998). Resistance to the OP insecticides azinphosmethyl and phosmet was expressed at low levels, chlorpyrifos was equally toxic to both resistant and susceptible populations, and acephate was more toxic to the resistant population than the susceptible population. Resistance to the methyl carbamates carbaryl and carbofuran was expressed at high levels and could not be quantified. There was no cross resistance to the pyrethroid cypermethrin. All of these observations indicated that the resistance was not different from that determined in the initial report (Pree et al. 1998). Additional tests with the neonicotinoids, imidacloprid, and acetamiprid, indicated these were equally toxic to both susceptible and resistant populations.

TABLE 3. Toxicity of insecticides to susceptible and resistant populations of Oriental fruit moth first instar larvae in 2004 compared to populations tested in 1994. Resistance ratio was calculated from LC_{50} resistant strain divided by LC_{50} susceptible strain. Resistance ratio calculated from LC_{50} resistant strain divided by LC_{50} susceptible strain.

Insecticide	Population (n=700)	Slope ± SE	LC_{50} (mg/L) (95% CL)	χ^2	Resistance Ratio 2004	Resistance Ratio 1994 Pree et al. (1998)
Azinphosmethyl	Susuceptible	4.6 ± 0.46	7.1 (6.6-7.6)	3.5		
	Resistant	4.3 ± 0.33	23.3 (20.5-25.9)	4.2	3.3	3.9
Phosmet	Susuceptible	4.0 ± 0.30	19.1 (17.6-20.6)	0.3		
	Resistant	3.4 ± 0.27	35.4 (32.0-38.7)	3.8	1.9	3.2
Chlorpyrifos	Susuceptible	4.5 ± 0.37	29.5 (25.6-33.1)	8.2		
	Resistant	3.8 ± 0.34	28.6 (24.2-32.6)	6.0	1.0	1.0
Acephate	Susuceptible	2.7 ± 0.24	203.3 (146.6-261.0)	12.4		
	Resistant	2.2 ± 0.21	87.4 (54.2-103.8)	6.8	0.4	0.4
Carbaryl	Susuceptible	4.4 ± 0.32	17.1 (14.5-19.6)	7.8		
	Resistant		>1000		>100	>100
Carbofuran	Susuceptible	2.6 ± 0.31	8.8 (6.0 - 11.4)	7.2		
	Resistant		>1000		>100	>100
Cypermethrin	Susuceptible	3.6 ± 0.32	0.88 (0.62-1.09)	10.5		
	Resistant	2.7 ± 0.20	1.03 (0.93-1.14)	3.5	1.2	1.0
Imidacloprid	Susuceptible	2.6 ± 0.23	2.0 (1.7-2.2)	2.0		
	Resistant	2.7 ± 0.27	2.0 (1.6-2.3)	3.9	1.0	n.a.
Acetamiprid	Susuceptible	3.8 ± 0.28	0.39 (0.29-0.49)	14.5		
	Resistant	3.2 ± 0.32	0.58 (0.47-0.69)	4.7	1.5	n.a.

Tests with insecticides incorporated into an artificial diet indicated that acetamiprid was equally toxic to both susceptible and resistant populations but that methoxyfenozide was slightly more toxic (1.7 fold) to the susceptible population (Table 4). By this procedure, methoxyfenozide was more toxic (to both susceptible and resistant populations) than acetamiprid. Resistance to methoxyfenozide, and to its analog tebufenozide, has been shown in populations of the obliquebanded leafroller *Choristoneura rosaceana* (Harris) (Lepidoptera: Tortricidae) that expressed resistance to OP insecticides (Waldstein et al. 1999; Pree et al. 2003).

Resistance mechanisms

Esterase activity in adult abdomens was higher by a factor of 1.6 in the resistant population (20.0 ± 2.8 μmoles min^{-1} mg^{-1} protein versus 12.5 ± 1.1 for the susceptible population). Differences between resistant and susceptible populations in 1994 (Kanga et al. 1997) were 3.9 fold. AChE activity was higher in both adult males and females of the resistant population (Table 5) but was not different between the sexes for either population. Measurements of AChE inhibition with carbaryl at 10^{-4} M indicated >90% inhibition in both sexes for the susceptible population and <20% inhibition of AChE in the resistant population. In earlier studies Kanga et al. (1997) reported no differences between populations in total AChE activity but did report large differences in inhibition between susceptible and resistant populations. Both elevated general esterases and the presence of an AChE insensitive to inhibition remain likely important factors in this resistance to OP and carbamate insecticides. We did not assay other possible resistance mechanisms. Elevated levels of oxidases and glutathione S-transferases were not shown to be involved in the resistance in earlier studies (Kanga et al. 1997).

Field tests of alternative insecticides

In small plot trials in 2002, methoxyfenozide applied at 360 g ai/ha was as effective as the standard chlorpyrifos or deltamethrin (Table 6). Lower rates of methoxyfenozide were less effective than the standards. Populations of Oriental fruit moth at this site were 40-55%

TABLE 4. Toxicity of insecticides incorporated into diet fed to susceptible and resistant populations of Oriental fruit moth larvae. Resistance ratio was calculated as LC_{50} resistant strain divided by LC_{50} susceptible strain.

Insecticide	Population (n=500)	Slope ± SE	LC_{50} mg/kg	χ^2	Resistance Ratio
methoxyfenozide	Susceptible	4.1 ± 0.41	0.028 (0.024-0.032)	9.3	
	Resistant	3.1 ± 0.23	0.049 (0.042-0.057)	5.8	1.7
acetamiprid	Susceptible	6.9 ± 0.73	0.45 (0.41-0.48)	6.6	
	Resistant	6.7 ± 1.07	0.48 (0.45-0.52)	12.2	1.1

TABLE 5. Inhibition of acetylcholinesterases in susceptible and resistant populations of Oriental fruit moth.

Population	Sex	Mean Rate ± SE 10^{-4} M Carbaryl μmoles/min/mg protein (n = 96-101)	Mean % Inhibition ± SE (n = 95-134 heads)
Susceptible	Male	28.1 ± 2.3 a[1]	91.0 ± 2.7
	Female	29.4 ± 3.8 a	91.7 ± 2.6
Resistant	Male	52.3 ± 4.8 b	17.2 ± 7.4
	Female	42.9 ± 4.3 b	15.8 ± 6.0

[1]Same letters are not significantly different (Tukey test (P<0.05)).

TABLE 6. Control of Oriental fruit moth damage on peach in small field plots, Jordan Station, ON, 2002. OFM Damage/Plot includes damage to twigs and fruit.

Treatment	Formulation	Rate a.i./ha	OFM Damage/Plot
Generation[1]			
chlorpyrifos	Lorsban 50WP	1700 g	2.8 c[2]
methoxyfenozide	Intrepid 2F	120 g	12.85 b
methoxyfenozide	Intrepid 2F	240 g	9.1 bc
methoxyfenozide	Intrepid 2F	360 g	8.5 bc
Control	-		24.0 a
Generation 2[3]			
deltamethrin	Decis 5EC	10 g	19.2 c[2,3]
methoxyfenozide	Intrepid 2F	120 g	127.0 b
methoxyfenozide	Intrepid 2F	240 g	127.0 b
methoxyfenozide	Intrepid 2F	360 g	101.5 bc
Control	-		239.5 a

[1] Applied 3 June 2002, to cv. Loring, Damage assessment 27 June 2002.
[2] Same letters are not significantly different (Tukey test, P<0.05).
[3] Applied 10 and 23 July 2002, to cv. Loring, Damage assessment 2 August 2002.

TABLE 7. Control of Oriental fruit moth damage on peach in small field plots, Jordan Station, ON, 2004. OFM Damage/Plot includes damage to twigs and fruit.

Treatment	Formulation	Rate a.i./ha	Total OFM Damage
Generation[1]			
deltamethrin	Decis EC	10 g	1.0 b[2]
acetamiprid	Assail 70WP	47.2 g	13.8 b
acetamiprid	Assail 70WP	168.8 g	11.5 b
acetamiprid	Assail 70WP	176 g	4.3 b
Control	-		30.3 a
Generation 2[3]			
deltamethrin	Decis 5EC	10 g	1.3 b
acetamiprid	Assail 70WP	47.2 g	3.0 b
acetamiprid	Assail 70WP	168.8 g	1.8 b
acetamiprid	Assail 70WP	172 g	1.5 b
Control	-		9.8 a

[1] Applied 21 May 2004, 124 DD base 7.2 °C after first male capture, cv. Elberta, Damage assessment 9 June 2004.

[2] Same letters are not significantly different (Tukey test, $P<0.05$).

[3] Applied 9 July 2004, 617 DD, base 7.2°C after first male capture, cv. Elberta, Damage assessment 22 July 2004.

resistant to OP insecticides and >5% were resistant to pyrethroids (Table 1). Infestations were higher in tests with the second generation in 2002. In similar tests in 2004 (Table 7), acetamiprid at three different rates was as effective as the standard deltamethrin.

In season long tests of various Oriental fruit moth control programs in 2003 and 2004 (Table 8) all of the programs effectively prevented damage to twigs by first generation larvae. As in most seasons, damage was less in generation 1 than later in the season. In 2003, in generation 2, damage to terminals was higher in methoxyfenozide-treated plots. This did not result in significantly higher damage at harvest although damage to fruit was slightly higher than the grower accepted threshold of 1%. In 2004 (Table 8) in generation 2, damage to terminals was again higher in methoxyfenozide-treated plots than in deltamethrin or acetamiprid-treated plots. At harvest, damage to fruit was higher in plots treated with methoxyfenozide in generations 2 and 3. All other programs had <1% fruit damaged at harvest.

In 2003, populations of European red mite did not reach threshold or action levels (5-10 mites/leaf in July) (Anonymous 2004) under any of the programs tested in 2003 (Table 9). Numbers of European red mites were higher in 2004 but did not exceed the economic threshold. However, in 2003, populations of the peach silver mite and numbers of beneficial mites were higher in all plots treated with deltamethrin. In 2004, numbers of peach silver

TABLE 8. Seasonal control of Oriental fruit moth (OFM) on peach, Jordan Station, ON, 2003-2004.

Program			Mean Damaged twigs/tree (± SE)		% Fruit Damaged At Harvest
	OFM Generation		OFM Generation		
1	2	3	1	2	
2003					
chlorpyrifos	deltamethrin	deltamethrin	1.0 ± 1.5 **a**[1]	1.2 ± 1.7 **a**	0.1 ± 0.3 **a**
chlorpyrifos	methoxyfenozide	methoxyfenozide	1.8 ± 1.8 **a**	9.8 ± 2.2 **b**	1.3 ± 1.7 **a**
methozyfenozide	deltamethrin	deltamethrin	1.7 ± 1.9 **a**	2.3 ± 2.4 **a**	0.7 ± 0.2 **a**
2004					
chlorpyrifos	deltamethrin	deltamethrin	1.9 ± 1.9 **a**[2]	5.0 ± 5.2 **b**	0.6 ± 0.6 **b**
methoxyfenozide	deltamethrin	deltamethrin	3.7 ± 2.2 **a**	3.0 ± 2.4 **b**	0.1 ± 0.2 **b**
methozyfenozide	acetamiprid	acetamiprid	4.4 ± 2.9 **a**	4.0 ± 3.1 **b**	0.5 ± 0.4 **b**
acetamiprid	methoxyfenozide	methoxyfenozide	4.2 ± 2.3 **a**	18.5 ± 11.5 **a**	3.1 ± 2.8 **a**

[1]For 2003, numbers in same column followed by same letter are not significantly different (Kruskal Wallis, $P<0.05$).

[2]For 2004, data were subjected to an ANOVA after log (x+1) transformation and differences between means separated by a Tukey test ($P<0.05$).

TABLE 9. Effects of Oriental fruit moth (OFM) control programs on populations of pest and beneficial mites Jordan Station, ON, 25 August 2003 and 25 August 2004.

Program			European red mites *Panonychus ulmi* (Koch) per 100 leaves Mean ± SE	Beneficial mites Acari: Phytoseidae per 100 leaves Mean ± SE	Peach Silver Mite Mean Rating/Sample
	OFM Generation				
1	2	3			
2003					
chlorpyrifos	deltamethrin	deltamethrin	5.3 **a**	15.3 **a**	4.97 **a**
chlorpyrifos	methoxyfenozide	methoxyfenozide	0 **a**	0.7 **b**	0.22 **b**
methoxyfenozide	deltamethrin	deltamethrin	9.0 **a**	16.3 **a**	4.65 **a**
2004					
chlorpyrifos	deltamethrin	deltamethrin	4.3 **a**	1.3 **a**	0.05 **a**
methoxyfenozide	deltamethrin	deltamethrin	156 **b**	3.3 **a**	0.5 **b**
methoxyfenozide	acetamiprid	acetamiprid	65.7 **ab**	61.3 **b**	1.5 **b**
acetamiprid	methoxyfenozide	methoxyfenozide	5.7 **a**	4.3 **a**	0 **a**

Numbers in the same column for each year followed by same letter were not significantly different (Tukey test, $P<0.05$).

mites did not increase as in 2003 and remained at low numbers in all plots. Beneficial mites were found in all plots but numbers were generally higher where phytophagous mites (either *P.ulmi* or *A. cornutus*) were available as a food source. In 2003, numbers of beneficial mites were higher in plots treated with deltamethrin in generations 2 and 3 of Oriental fruit moth, plots which held large numbers of peach silver mites. In 2004, numbers of beneficial mites were highest in plots treated with acetamiprid in generations 2 and 3.

Discussion

The initial goal of the resistance management strategy for Oriental fruit moth established after the episode of resistance to OP insecticides in 1993-1994 was to maintain susceptibility to pyrethroids, the only effective alternative at that time. That program appears to have been successful. The percentage of the population expressing resistance to pyrethroids declined from levels reported in earlier studies and resistance to pyrethroids was not found at all sites. Resistance to OP insecticides was found at all sites and was at a higher frequency than previously reported at one extensively monitored site. This occurred despite avoidance of the OP insecticides, azinphosmethyl and phosmet, that had previously been used on peach for control of Oriental fruit moth. Chlorpyrifos was equally toxic, as in previous studies, to both resistant and susceptible populations. In the last 10 years, the Oriental fruit moth has become a pest on apples where OP insecticides have continued to be used for other pests and this may be the source of OP resistant insects. Pyrethroids are not used extensively on apples.

The potential impact of the impending removal of chlorpyrifos after 2006 may be ameliorated by the use of either methoxyfenozide or the neonicotinoid acetamiprid. The cross resistance to methoxyfenozide identified here was expressed at low levels (1.7 fold at the LC_{50}) and, at higher rates, this compound effectively controlled Oriental fruit moth in both small plot and program trials against the first generation. Later applications against the second and third generations, especially in the program trials, were less effective. Acetamiprid was effective throughout the season. If methoxyfenozide were reserved as a replacement for chlopyrifos for use against generation 1, this would hold the neonicotinoid acetimiprid and/or pyrethroids or rotations of these two groups for the rest of the season. The use of pyrethroids in IPM programs has often been discouraged because of their impact on beneficial mites and the associated outbreaks of phytophagous mites (Croft 1990). In the program trials reported here, numbers of European red mites did not exceed acceptable thresholds but high populations of peach silver mites were associated with pyrethroid use in 2003. Further evaluation of the impact of these products on beneficial mite populations in peach and apple ecosystems is necessary but Beers et al. (2005) have shown increased populations of phytophagous mites following repeated applications of various neonicotinoids. In any case, the addition of these two new insecticides will provide an opportunity not only to manage or prevent resistance to pyrethroids, but if all three groups of chemicals are utilized, should also delay the development of resistance to these new products. There is also an alternative control program (Trimble et al. 2001) that involves the integration of insecticides for the first generation with mating disruption for later generations. That program would likely provide the best long-term resistance management strategy for

Oriental fruit moth on peach in Ontario.

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References

Anonymous. 2004. Fruit production recommendations 2004. Ontario Ministry of Agriculture, Food and Rural Affairs. Publication 360. 294 pp.

Beers, E. H., J. F. Brunner, J. E. Dunley, M. Doerr, and K. Granger. 2005. Role of neonicotinyl insecticides in Washington apple integrated pest management. Part II. Nontarget effects on integrated mite control. Journal of Insect Science 5: 16.

Bradford, M. M. 1976. A rapid and sensitive method for quantification of microgram quantities of protein utilizing the principle of protein-dye binding. Analytical Biochemisty 72: 248-254.

Croft, B. A. 1990. Arthropod biological control agents and pesticides. Wiley Interscience Publishers, New York.

Ellman, G. L., K. D. Courtney, V. Andres Jr., and R. M. Featherstone. 1961. A new rapid colorimetric determination of cholinesterase activity. Biochemical Pharmacology 7: 88-95.

Henderson, C. F. and H. V. McBurnie. 1943. Sampling technique for determining populations of the citrus red mite and its predators. U.S.D.A. Circular 671.

Herath, P. R. J., J. Hemingway, I. S. Weerasingh, and K. G. I. Jayawardena. 1987. The detection and characterization of malathion resistance in field populations of *Anopheles culifacies* B in Sri Lanka. Pesticide Biochemistry and Physiology 29: 157-162.

Kanga, L. H. B. and F. W. Plapp Jr. 1995. Development of a technique to monitor resistance in field populations of tobacco budworm. Journal of Economic Entomology 88: 487-494.

Kanga, L. H. B., D. J. Pree, J. L. vanLier, and K. J. Whitty. 1997. Mechanisms of resistance to organophosphorus and carbamate insecticides in Oriental fruit moth populations (*Grapholita molesta* Busck). Pesticide Biochemistry and Physiology 59: 11-23.

Kanga, L. H. B., D. J. Pree, and J. L. vanLier. 1999. Monitoring for resistance to organophosphorus and carbamate insecticides in the Oriental fruit moth (Lepidoptera: Tortricidae). Canadian Entomologist 131: 441-450.

Kanga, L. H. B., D. J. Pree, J. L. vanLier, and G. M. Walker. 2003. Management of insecticide resistance in Oriental fruit moth (*Grapholita molesta*;Lepidoptera: Tortricidae) populations from Ontario. Pest Management Science 59: 921-927.

Moores, G. D., A. L. Devonshire, and I. Denholm. 1988. A microtitre plate assay for characterizing insensitive acetylcholinesterase genotypes of insecticide resistant

insects. Bulletin of Entomological Research 78: 537-544.

Pest Management Regulatory Agency. 2003. Phase 2 of the re-evaluation of chlorpyrifos. PACR 2003-03. 56 pp.

Phillips, J. H. H. 1973. Monitoring for the Oriental fruit moth with synthetic sex pheromone. Environmental Entomology 2: 1039-1042.

Pree, D. J. 1979. Toxicity of phosmet, azinphosmethyl and permethrin to the Oriental fruit moth and its parasite, *Macrocentrus ancylivorus*. Environmental Entomology 8: 969-972.

Pree, D. J., D. H. C Herne, J. H. H. Phillips, and W. P. Roberts. 1983. Pest management program for peach series: Oriental fruit moth. OMAF Agdex 212/624 83-027.

Pree, D. J. 1985. *Grapholita molesta*. pp. 307-311 *In* Handbook of Insect Rearing, Vol. 2, Singh, P. and R.F. Moore (eds.) Elsevier, Amsterdam.

Pree, D. J., K. J. Whitty, L. Van Driel ,and G. M. Walker. 1998. Resistance to insecticides in Oriental fruit moth populations (*Grapholita molesta*) from the Niagara peninsula of Ontario. Canadian Entomologist 130: 245-256.

Pree, D. J., K. J. Whitty, L. A. Bittner, and M. K. Pogoda. 2003. Mechanisms of resistance to organophosphorus insecticides in populations of the obliquebanded leafroller *Choristoneura rosaceana* (Harris) (Lepidoptera: Tortricidae) from southern Ontario. Pest Management Science 59: 79-84.

Rice, R. E., W. W. Barnett, D. L. Flaherty, W. J. Bentley, and R. A. Jones. 1982. Monitoring and modeling oriental fruit moth in California. California Agriculture Jan-Feb 1982. 11-12.

Tabashnik, B. E., A. L. Patin, T. J. Dennehy, Y-B Liu, Y. Carriere, M. A. Sims, and L. Antilla. 2000. Frequency of resistance to *Bacillus thuringiensis* in field populations of pink bollworm. Proceedings of the National Academy of Sciences 97: 12980-12984.

Trimble, R. M., D. J. Pree, and N.J. Carter. 2001. Integrated control of Oriental fruit moth (Lepidoptera:Tortricidae) in peach orchards using insecticide and mating disruption. Journal of Economic Entomology 94: 476-485.

Waldstein, D. E., W. H. Reissig, J. G. Scott, and R. W. Straub. 1999. Susceptibility of obliquebanded leafroller (Lepidoptera: Tortricidae) populations from commercial apple orchards and an unsprayed habitat in New York to tebufenozide. Journal of Economic Entomology 96: 1251-1255.

Yokoyama, V. Y., G. T. Miller and J. M. Harvey. 1987. Development of Oriental fruit moth on a laboratory diet. Journal of Economic Entomology 80: 272-276.

INFLUENCE OF GREENHOUSE MICROCLIMATE ON *NEOSEIULUS (AMBLYSEIUS) CUCUMERIS* (ACARI: PHYTOSEIIDAE) PREDATION ON *FRANKLINIELLA OCCIDENTALIS* (THYSANOPTERA: THRIPIDAE) AND OVIPOSITION ON GREENHOUSE CUCUMBER

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Abstract *J. ent. Soc. Ont.* 136: 71–83

The influence of leaf boundary layer vapor pressure deficit (VPD) and leaf temperature on the predation rate by *Neoseiulus (Amblyseius) cucumeris* (Oudemans) (Acari: Phytoseiidae) on *Frankliniella occidentalis* (Pergande) (Thysanoptera: Thripidae) and on the oviposition rate by *N. cucumeris* on cucumber leaves were determined for greenhouse cucumber grown under semi-commercial production conditions. Vapor pressure deficit did not affect either the predation or oviposition rates by *N. cucumeris*. Examination of ambient and boundary layer VPDs revealed that it was difficult to produce substantial changes in boundary layer VPD in high-gutter greenhouses. Therefore, the relatively steady state of humid conditions at the leaf boundary layer resulted in no significant differences in predation and oviposition rates despite changes in ambient VPD. However, leaf temperature did influence the predation and oviposition rates by *N. cucumeris*: both rates increased at the higher temperature. This suggests that establishing seasonal release rates should result in increased efficiency of this predator during the cooler periods of the year.

Introduction

The predatory mite *Neoseiulus (Amblyseius) cucumeris* (Oudemans) (Acari: Phytoseiidae) is an important biological control agent used to control *Frankliniella occidentalis* (Pergande) (Thysanoptera: Thripidae) on greenhouse cucumbers worldwide (Ramakers and O'Neill 1999; Shipp and Ramakers 2004). *Neoseiulus cucumeris* feeds primarily on first instar *F. occidentalis*, and adult female mites have been reported in

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laboratory trials at 25-26°C to reach a predation plateau of between 4.4 and 6.9 first instars per day on cucumber leaf disks (Shipp and Whitfield 1991; van Houten et al. 1995a; 1995b). However, the predation rate of the nymphal stages of *N. cucumeris* on *F. occidentalis* is more complex and often depends on the presence of an adult *N. cucumeris* to assist in killing the larger prey host or to share a killed first instar (Cloutier and Johnson 1993). Control of *F. occidentalis* at the recommended rates for release of *N. cucumeris* is often not achieved until 5-6 weeks after the mites are released into the greenhouse (Shipp et al. 1996).

Improving the predation efficiency of *N. cucumeris* should result in faster, more effective control of *F. occidentalis* populations. Abiotic conditions such as temperature and humidity influence the rate of predation by mites (Stenseth 1979; Ball 1980; Everson 1980; Hardman and Rogers 1991). Higher temperatures are believed to cause greater predation rates as a result of the increased energy demand of the predator, which translates behaviorally into hunger and its associated activities, such as foraging (Everson 1980). Laboratory evidence indicates that vapor pressure deficit (VPD) (i.e., the difference between saturate and actual water vapor pressure at a specific air temperature) affects predation rates as well. Stenseth (1979) reported that *Phytoseiulus persimilis* Athias-Henriot (Acari: Phytoseiidae) provides more effective control of *Tetranychus urticae* (Koch) (Acari: Tetranychidae) at higher temperatures and humidities (27°C and 70-85% RH). The predation rate by *N. cucumeris* on *F. occidentalis* was strongly influenced by VPD in laboratory trials (Shipp et al. 1996). A quadratic model fitted to the predation responses of adult *N. cucumeris* on first instar *F. occidentalis* over a VPD range of 0.4-3.94 kPa showed that the greatest predation rates occurred at either end of the VPD range.

The efficacy of a biological control agent also depends on its ability to reproduce in its environment. Several factors can affect the ovipositional behaviour of predatory mites. A mated *N. cucumeris* can oviposit 1.3 to 2.5 eggs per day depending on plant host, climate, and food (Castagnoli and Simoni 1990; Castagnoli and Liguori 1991; van Houten et al. 1995a; 1995b).

In the past, the majority of studies examining the influence of temperature and humidity on predation and oviposition rates were conducted in controlled environment chambers in order to precisely control the climatic parameters being investigated. However, insects and mites usually spend most of their time within the boundary layer of plant leaves (i.e., 0.5-5.0 mm from the leaf surface depending on wind speed, leaf shape, size, and hairiness), which can have temperature and humidity conditions that are quite different from greenhouse ambient conditions (Nobel 1974; Ferro and Southwick 1984). Ferro et al. (1979) showed that leaf temperatures on apple trees could reach 25°C on cool, clear days while ambient air temperature was only 15°C. Conversely, on hot sunny days when the air temperature was 39°C, leaf temperature was only 26°C. The changes between greenhouse macroclimate and microclimate at the plant surface are not as great as in the field situation since the climate in the greenhouse can be controlled using computerized climate control systems. However, the macroclimate in the greenhouse can be very different from the microclimate at the phyllopane (leaf surface) due to thermal, concentration, and velocity boundary layers that can result in steep gradients in temperature, VPD, and CO_2 (Jewett and Jarvis 2001). Boulard et al. (2002), in studying the influence of tomato leaf boundary layer climate on the implications of microbial control of whiteflies, found that relative humidity measured at 5 mm from the leaf surface in a tomato greenhouse could be 20-30% greater than ambient

measurements. The objectives of the present study were to determine the influence of boundary layer VPD and leaf temperature on the rate of predation by *N. cucumeris* on *F. occidentalis*, and on the oviposition rate by *N. cucumeris* on greenhouse cucumber.

Methods

Experimental treatments

Trials were conducted at the Greenhouse and Processing Crops Research Centre, Harrow, Ontario on greenhouse cucumber (*Cucumis sativus* L.) (cv. Bodega) in three glasshouse compartments (7x13 m) from May 2000 to September 2001. A planting density of 1.5 plants/m^2 (seven double rows with 10 plants/row/compartment) was used for all trials. The outside rows and end plants for each row served as guard plants and were not used in any measurements. The Harrow Fertigation Manager (Climate Control Systems Inc., Leamington, ON) was used to irrigate and fertilize the plants according to commercial recommendations (Ontario Ministry of Agriculture and Food 2001).

Three ranges of ambient VPD treatments were evaluated at each of two ambient temperatures regimes to simulate winter crop production conditions (21°C day and 20°C night) and summer conditions (25°C day and 22°C night) as measured at top canopy height (2.2 m). It was not possible to use exactly the same ambient VPD values for the range of humidity treatments for the summer and winter trials because greenhouse ambient VPD is directly affected by outside humidity conditions. However, the differences among ambient VPD treatment values at the top canopy among the three greenhouses for the summer and winter trials were essentially similar (0.26-0.65 kPa) over all trials. The three VPD treatments were achieved by randomly assigning one of three humidity settings to each of the three greenhouses that were set at the same temperature regime (summer or winter production conditions). Thus, each trial consisted of three greenhouses at the same ambient temperature (21 or 25°C), but with each greenhouse at a different humidity. The trials were replicated over time. An Argus Greenhouse Climate Management System (Argus Control System Ltd., White Rock, BC) was used to maintain set point temperature and humidity conditions at the top canopy height.

All predation trials were conducted on the undersurface of leaves at two heights in the canopy (middle: 1.5 m, top: 2.2 m) and oviposition trials were conducted at one height in the canopy (middle: 1.5 m). VPD values at middle canopy were always higher than at top canopy. This relationship is common in greenhouse vegetables due to the lower light intensity and wind velocity within the canopy and has been shown for both low and high-gutter greenhouses (Jewett and Jarvis 2001; Zhang and Shipp 2002). At mid-canopy height in each greenhouse, ambient temperature and humidity were measured with a Hycal temperature/humidity probe (Hycal Co., El Monte, CA). Leaf temperatures were monitored using infra-red thermocouple (IRt) sensors (Omega, Laval, PQ), that were placed 1-2 cm from the leaf surface. These climate parameters (ambient temperature and humidity, and leaf surface temperature) in combination with the greenhouse cucumber plant surface climate model (PSCLIMATE) developed by Zhang et al. (2002), were used to calculate ambient and boundary layer VPDs.

Predation trials with *Neoseiulus cucumeris*

A single, 1-2 day old, mated female mite and 15 first instar *F. occidentalis* were placed on the undersurface of a cucumber leaf in a plexiglass clip cage (0.7x4.0 cm) (Fig. 1). The cage had thrips-proof screening on one end on the lower surface of the leaf and a padded plastic plate on the top of the leaf. A fold back clip was used to hold together both pieces of the cage. To ensure that all test mites were at the same age, eggs of *N. cucumeris* were collected by sifting commercially purchased cultures of Thripex-plus (Koppert Canada, Leamington, ON) using a fine mesh screen. Eggs that passed through the screen were collected on the bottom of a 9 cm Petri dish and were placed using a moistened camel's hair brush on the ventral side of a kidney bean (*Phaseolus vulgaris* L.) leaf. The leaf was then floated on distilled water on the bottom of a 14 cm Petri dish to maintain a high humidity and to prevent the mites from leaving the leaf. The leaf was held in the centre of the dish by placing TangleFoot (Adhesive Pest Management and Tree Protection Products, Grand Rapids, MI) between the leaf and the bottom of the dish. Cohorts of 30 eggs were placed beneath a small piece of leaf (20 mm^2) that was placed at the centre of each larger leaf. The dishes were incubated at 25 ± 1°C and L12:D12. The mites were fed frozen first and second instar *F. occidentalis* daily and were transferred to a new leaf after each molt. Adults appeared approximately 5-6 days after hatching. To ensure mating and starvation, the mites

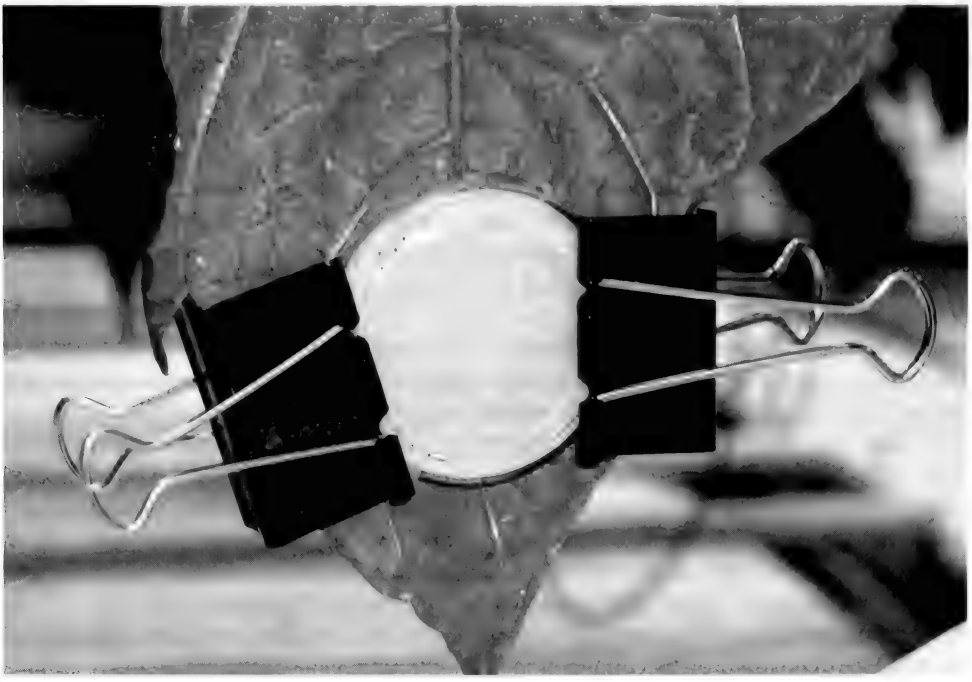

FIGURE 1. Screen leaf cage used in the predation and oviposition trials as viewed on the undersurface of a cucumber leaf.

were placed in a vial (1 female: 1 male) without food for 24 h before a trial.

First instar *F. occidentalis* were used in the predation trials, as this is the preferred prey stage for *N. cucumeris* (Shipp and Whitfield 1991). To obtain first instars, adult *F. occidentalis* were placed on the ventral side of kidney bean leaves that were placed on a piece of filter paper and cotton, saturated with distilled water, on the bottom of a 9 cm Petri dish. A Petri dish cover with thrips-proof screening on one end was placed over the Petri dish and secured with a large, fold-back clip to confine the *F. occidentalis*. The Petri dish was placed in a controlled environmental chamber at 27 ± 1°C and 80% RH. The adults were removed after 24 h and first instar *F. occidentalis* were removed with a moistened camel's hair brush approximately 3-4 days later.

The predation trials were conducted for 24 h, after which the cage and leaf area inside the cage were removed and examined using a dissecting microscope (50X magnification) for the number of dead and live thrips. A thrips was considered dead, if it was shriveled or did not move when touched with a probe. The status of the mite (live or dead) also was noted and any cages in which the mite was dead were not included in the data analysis. For each trial, a leaf cage was also set up with 15 first instar thrips and no predatory mites at each canopy height for each VPD treatment to determine the survival rate of *F. occidentalis* over the 24 h predation period. Predation trials were replicated six to nine times for each temperature and VPD treatment over the summer and winter crop production periods with two to four cages per plant height (middle and top canopy) in each trial. For each predation trial, middle and top canopy leaf cages were paired together on the same plant. Different cucumber plants were used for each pairing and for each trial.

Oviposition trials with *Neoseiulus cucumeris*

A single 1-2 day old, mated female *N. cucumeris* which was starved for 24 h was transferred to the undersurface of a cucumber leaf at middle canopy in each of the treatment greenhouses. The same cages as those used in the predation trials were set up with one *N. cucumeris* per cage per treatment. Frozen second instar *F. occidentalis*, in excess of what a mite would consume (>10 thrips/mite/day), were placed in the cage as food. Every 24 h for 7 days, the leaf and cage were examined using a dissecting microscope (50X magnification), and the number of oviposited eggs and status of the mites (live, dead, or missing) was recorded. For examination of the leaf cage, the leaf area around the cage was cut and the cage and excised leaf area were returned to the laboratory for observation. After checking the leaf and cage, the cage and mite were placed on a new leaf in the same greenhouse. Cages that had missing mites were discarded. This procedure was replicated three times at each temperature and VPD treatment with 8-10 cages per replication.

Data analysis

All count data were square root transformed before analysis; untransformed data are reported in the tables and graphs. The impact of leaf surface temperature, crop canopy height, and leaf boundary layer VPD on the daily predation rate (prey/predator/day) by *N. cucumeris* on *F. occidentalis*, and on the oviposition rate (eggs/female/day) by *N. cucumeris* was analyzed using an ANCOVA. The ANCOVA was conducted with temperature and canopy height as the main factors for the predation trials, with temperature as the main factor for the ovipositional trials, and VPD as the covariate factor for both experiments

(PROC GLM, SAS Institute 1995).

Results and Discussion

Influence of vapor pressure deficit on predation and oviposition rates of *Neoseiulus cucumeris*

Mean (± SE) ambient temperatures and corresponding leaf boundary layer VPDs and leaf temperatures for the predation and oviposition trials are presented in Table 1. The survival rate for first instar *F. occidentalis* that were placed in the control leaf cages was always greater than 97.5%, indicating essentially zero mortality of the first instars when *N. cucumeris* was not present in the leaf cages. ANCOVA showed that the predation rate of *N. cucumeris* at the top and middle canopy heights was not significantly different ($F_{1,81}$= 1.76, P= 0.19) (Table 2). The mean numbers of first instar *F. occidentalis* killed by *N. cucumeris* were not significantly affected by the leaf boundary layer VPDs ($F_{1,81}$= 1.42, P= 0.24) (Table 2). All first and second order interactions were also not significant.

Previous studies found that mite predation rates can be affected by different air humidity regimes (Mori and Chant 1966a; Shipp et al. 1996; Rott and Ponsonby 2000). At high VPDs (low humidities), mites become dehydrated and as a result, feed more to compensate for this loss of water (Boudreaux 1958). Mori and Chant (1966b) found that the predatory mite, *P. persimilis*, and its prey, *T. urticae*, are more active at higher VPDs which results in more frequent encounters between predator and prey and thus higher rates of predation. However, Shipp et al. (1996) reported that first instars of *F. occidentalis* were less active at high VPDs, while *N. cucumeris* remained active. *Neoseiulus cucumeris* ceased moving after 12 h at VPDs ≥ 2.12 kPa. In the present study, leaf surface VPDs were always low (< 0.69 kPa) and thus, the mites or thrips were not exposed to dehydrating water stress conditions. In addition, the thrips could obtain water by feeding on the cucumber leaves.

The results from Shipp et al. (1996) indicated that even over the limited VPD range tested in the present greenhouse trials, predation rates should have increased with decreased VPD. In the controlled environmental chamber trials, temperature and VPD were constant, but in the greenhouse trials, VPDs fluctuated slightly (up to ± 7%). Kramer and Hain (1989) and van Houten and van Lier (1995) reported that mite survival increased when mites were exposed to fluctuating versus constant humidity conditions. Also, due to reduced air movement in the cage compared to an open leaf, the boundary layer in the leaf cages may be slightly greater than would be predicted using the PSCLIMATE model to determine VPD at the leaf surface. However, the basic premise for air movement in a boundary layer is "still" air.

The effect of leaf boundary layer VPDs on the number of eggs oviposited daily by *N. cucumeris* was also not significant ($F_{1,14}$=1.21, P= 0.29) (Table 3). There is no published information on the effect of VPD on the oviposition rate of predatory mites, although laboratory trials have found that *Tetranychus* spp. have an increased oviposition rate under "dry" conditions (Boudreaux 1958). The range of boundary layer VPDs in our study was probably too narrow to detect any influence of VPD on oviposition rates by *N. cucumeris*.

TABLE 1. Mean (± SE) ambient and corresponding leaf boundary-layer vapor pressure deficits (VPD) and leaf temperatures used in A. *Neoseiulus cucumeris* predation trials; and B. *N. cucumeris* oviposition trials.

Trial	Canopy height	Ambient temp. (°C)	Ambient VPD (kPa) in three greenhouses			Leaf temp. (°C)	Boundary layerVPD (kPa) in three greenhouses		
A	Top	21.0 ± 0.23	0.35 ± 0.020	0.64 ± 0.018	0.96 ± 0.054	20.0 ± 0.38	0.09 ± 0.005	0.25 ± 0.014	0.43 ± 0.030
	Middle	21.6 ± 0.24	0.67 ± 0.035	1.08 ± 0.041	1.32 ± 0.027	20.8 ± 0.24	0.24 ± 0.017	0.42 ± 0.021	0.69 ± 0.015
	Top	24.5 ± 0.50	0.26 ± 0.008	0.52 ± 0.012	0.81 ± 0.017	23.7 ± 0.55	0.13 ± 0.005	0.22 ± 0.010	0.35 ± 0.009
	Middle	24.9 ± 0.48	0.79 ± 0.013	0.98 ± 0.015	1.25 ± 0.029	23.7 ± 0.48	0.27 ± 0.011	0.36 ± 0.009	0.60 ± 0.016
B	Middle	21.6 ± 0.30	0.42 ± 0.003	0.69 ± 0.007	0.84 ± 0.011	20.1 ± 0.26	0.11 ± 0.001	0.28 ± 0.003	0.50 ± 0.002
		25.2 ± 0.54	0.78 ± 0.009	0.99 ± 0.050	1.29 ± 0.006	24.0 ± 0.51	0.31 ± 0.003	0.40 ± 0.002	0.63 ± 0.004

Top = 2.2 m and Middle = 1.5 m. Oviposition trials were only performed at middle canopy.

TABLE 2. ANCOVA for the effect of temperature and canopy height (main factors) and leaf bounder layer VPD (covariate) on the daily predation rate (number of first instar *Frankliniella occidentalis*/female/day) by *Neoseiulus cucumeris*.

Effect	df	*F*	Probability
Temperature	1	25.87	< 0.0001
Height	1	1.76	n.s.
Temp*Height	1	0.33	n.s.
VPD	1	1.42	n.s.
VPD*Temp	1	0.05	n.s.
VPD*Height	1	1.39	n.s.
VPD*Temp*Height	1	0.67	n.s.
Error	81		

TABLE 3. ANCOVA for the effect of temperature (main factor) and leaf boundry layer VPD (covariate) on the daily oviposition rate (number of eggs/female/day) by *Neoseiulus cucumeris*.

Effect	df	*F*	Probability
Temperature	1	12.18	0.0036
VPD	1	1.21	n.s.
VPD*Temperature	1	0.18	n.s.
Error	14		

Examination of VPD data during the trials reveals how stable boundary layer VPD is without extreme changes in the ambient conditions (Table 1). Extreme climate changes are detrimental to greenhouse crop production, and it is believed that the use of high-gutter (4.2-5.4 m) greenhouses have substantially reduced the occurrence of extreme fluctuation in greenhouse climate due to a "buffer" layer of air between the crop and the outside of the greenhouse (Jewett and Jarvis 2001; Hao et al. 2005). Thus, in high-gutter greenhouse vegetable production systems as used in this study, ambient VPDs for recommended commercial production practices (0.4-0.8 kPa [Ontario Ministry of Agriculture and Food 2001]) have a minimal impact on plant boundary layer VPD, which is usually in a range that seems to be too small to have a significant impact on predation or oviposition rates by *N. cucumeris*. However in low-gutter greenhouses (< 2.5 m), especially with side ventilation, boundary layer VPD is much more impacted by ambient VPD and can even approach ambient conditions depending on wind speed (Boulard et al. 2004).

Influence of temperature on predation and oviposition rates of *Neoseiulus cucumeris*

ANCOVA of the predation data showed that the mean number of first instar *F. occidentalis* killed by *N. cucumeris* was significantly influenced by leaf temperature ($F_{1, 81} = 25.87$, $P < 0.0001$) (Table 2). A predation rate of 8.5-8.7 thrips/day at 24°C was approximately double the rate at 20°C. The increase in predation rate with increased temperature corresponds with laboratory trials conducted on different leaf surfaces with other predatory mite species (Stenseth 1979; Ball 1980; Everson 1980; Hardman and Rogers 1991). Leaf temperature influences the body temperature of the predatory mite as well as the food conversion rate (Sabelis 1981). Temperature has been shown to affect the rate of gut emptying, the attack rate, and handling time of the prey (Thompson 1978, Everson 1980; Sabelis 1981). Higher temperatures increase the metabolic rate of predators and thereby decrease the digestive pause between prey (Nakamaru 1977). Hungry predators have more successful capture rates, are more active, and search more vigorously for prey (Sandness and McMurtry 1972). Under higher temperatures, *N. cucumeris* is more active than *F. occidentalis* (Shipp et al. 1996; T. Jones, unpublished data) and would probably have more frequent encounters with *F. occidentalis*, resulting in an increased predation rate.

The mean number of eggs oviposited by *N. cucumeris* was also influenced by temperature (Table 3). *Neoseiulus cucumeris* oviposited a significantly greater number of eggs at the higher temperature when compared to the lower temperature range ($F_{1,14} = 12.18$, $P = 0.0036$) (Table 4). van Houten et al. (1995a) and Gillespie and Ramey (1988) observed oviposition rates of 2.2 and 1.5 eggs/day at 25 and 20°C respectively, for *N. cucumeris*. This relationship is the result of proportionately decreased digestion time and increased predation rate at higher temperatures. The increased predation at higher temperatures provides the mite with the increased energy required for the higher egg production.

TABLE 4. Number of first instar *Frankliniella occidentalis* (mean ± SE) killed over a 24 h period by *Neoseiulus cucumeris* and the number of eggs laid by female *N. cucumeris* at two leaf temperatures.

Leaf temperature (°C)	Canopy height	Predation rate (prey/day)	n[1]	Oviposition rate (eggs/female/day)	n[2]
24	Top	8.5 ± 0.30 a	21	--	
	Mid	8.7 ± 0.46 a	19	2.14 ± 0.05 a	9
20	Top	4.3 ± 0.26 b	25	--	
	Mid	4.4 ± 0.24 b	24	1.37 ± 0.05 b	9

[1] Number of replicates over time with two to four cage observations each trial per greenhouse.
The initial prey density is 15 thrips per cage.

[2] Number of replicates over time with eight to ten cage observations each trial.
Within each column, means followed by different letters are significantly different at $P < 0.05$.

Previous studies investigating the interactions between climate (temperature and humidity) and predation and oviposition rates by greenhouse predatory mites were all conducted under controlled conditions in the laboratory. It is important to test these relationships under conditions that are more similar to commercial production conditions to ensure that the relationships are still valid. The present experiment is the first study to evaluate the influence of leaf temperature and boundary layer VPD on predation and oviposition rates by *N. cucumeris* on a greenhouse crop (cucumber) under semi-commercial production conditions. Under high-gutter greenhouse production conditions, boundary layer VPD varied very little from 0.1-0.7 kPa. At this range, VPD did not have a significant impact on predation or oviposition rates by *N. cucumeris*. The range for leaf boundary layer VPD can be much greater under low-gutter greenhouse production conditions, especially with side ventilation (Boulard et al. 2004). Leaf temperature did have a significant impact on predation and oviposition rates by *N. cucumeris*.

In summary, the current introduction rates of *N. cucumeris* for *F. occidentalis* do not consider greenhouse climatic or plant surface microclimatic conditions when recommendations are made to growers. Usually an introduction rate is recommended depending on the crop and/or the level of thrips infestation, irrespective of the time of year. This study demonstrated that plant surface microclimate can have a significant impact on the effectiveness of predatory mites. Leaf surface temperatures of cucumber plants were different from ambient air temperatures, but were within about 1 ± 0.5°C of ambient temperature (Table 1). Greenhouse climate is accurately controlled using computerized climate control systems and can be maintained within narrow limits (±1°C) within commercial greenhouses. The 24 h temperature regimes used in our study corresponds to climate conditions in greenhouse cucumber crops during the winter and summer in Ontario. However, similar seasonal differences occur for other greenhouse cucumber production areas in temperate climate regions.

Based on the results from this study, *N. cucumeris* will provide the most effective control of *F. occidentalis* when conditions are near the higher end of recommended production temperatures for cucumbers (17-25°C (Ontario Ministry of Agriculture and Food 2001)). Growers often state that thrips control during the winter months is not as effective as during summer, or that it takes too long (Shipp, unpublished data). Therefore, during winter conditions when temperatures are lower, growers should introduce mites more frequently into the greenhouse. Increased knowledge and understanding of greenhouse climate and plant surface microclimate, and their effect on insect and mite biology/behaviour will result in improved effectiveness of biological control programs for greenhouse crops.

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References

Ball, J. C. 1980. Development, fecundity, and prey consumption of four species of predacious mites (Phytoseiidae) at two constant temperatures. Environmental Entomology 9: 298-303.

Boudreaux, H. B. 1958. The effect of relative humidity on egg-laying, hatching, and survival in various spider mites. Journal of Insect Physiology 2: 65-72.

Boulard, T., M. Mermier, J. Fargues, N. Smits, M. Rougier, and J.C. Roy. 2002. Tomato leaf boundary layer climate: implications for microbiological whitefly control in greenhouses. Agriculture and Forest Meteorology 110: 159-176.

Boulard, T., H. Fatnassi, J. C. Roy, J. Lagier, J. Fargues, N. Smits, M. Rougier, and B. Jeannequin. 2004. Effect of greenhouse ventilation on humidity of inside air and in leaf boundary-layer. Agriculture and Forest Meteorology 125: 225-239.

Castagnoli, M. and S. Simoni. 1990. Biological observations and life table parameters of *Amblyseius cucumeris* (Oudemans) (Acarina: Phytoseiidae) reared on different diets. Redia 73: 569-583.

Castagnoli, M. and M. Liguori. 1991. Laboratory observations on duration of copulation and egg production of three Phytoseiid species fed on pollen. pp. 231-239 *In* The Acari: Reproduction, Development and Life History Strategies. Schuster R. and Murphy P.W. (eds.) Chapman and Hall, London. 554 pp.

Cloutier, C. and S. G. Johnson. 1993. Interaction between life stages in a phytoseiid predator: western flower thrips prey killed by adults as food for photonymphs of *Amblyseius cucumeris*. Experimental and Applied Acarology 17: 441-449.

Everson, P. 1980. The relative activity and functional response of *Phytoseiulus persimilis* (Acarina: Phytoseiidae) and *Tetranychus urticae* (Acarina: Tetranychidae): The effect of temperature. The Canadian Entomologist 112: 17-24.

Ferro, D, R. B. Chapman, and D. R. Penman. 1979. Observations on insect microclimate and insect pest management. Environmental Entomology 8: 1000-1003.

Ferro, D. N. and E. E. Southwick. 1984. Microclimate of small arthropods: estimating humidity within the leaf boundary layer. Environmental Entomology 13: 926-929.

Gillespie, D. R. and C. A. Ramey. 1988. Life history and cold storage of *Amblyseius cucumeris* (Acarina: Phytoseiidae). Journal of Entomological Society of British Columbia 85: 71-76.

Hao, X., T. Jewett, J. Zheng, and S. Khosla. 2005. Microclimate and energy consumption in commercial, hot-water and steam heated greenhouses for tomato production. Acta Horticulturae 691: 171-178.

Hardman, J. M. and M. L. Rogers. 1991. Effects of temperature and prey density on survival, development, and feeding rates of immature *Typhlodromus pyri* (Acari: Phytoseiidae). Environmental Entomology 20: 1089-1096.

Jewett, T. J. and W. R. Jarvis. 2001. Management of the greenhouse microclimate in relation to disease control: a review. Agronomie 21: 351-366.

Kramer, D. A. and F. P. Hain. 1989. Effect of constant- and variable-humidity and temperature regimes on the survival and developmental periods of *Oligonychus ununguis* (Acarina: Tetranychidae) and *Neoseiulus fallacis* (Acarina: Phytoseiidae). Environmental Entomology 18: 741-746.

Mori, H. and D. A. Chant. 1966a. The influence of prey density, relative humidity, and starvation on the predaceous behaviour of *Phytoseiulus persimilis* Athias-Henriot (Acarina: Phytoseiidae). Canadian Journal of Zoology 44: 483-491.

Mori, H. and D. A. Chant. 1966b. The influence of humidity on the activity of *Phytoseiulus persimilis (*Athias-Henriot) and its prey, *Tetranychus urticae* (C. L. Koch) (Acarina: Phytoseiidae, Tetranychidae). Canadian Journal of Zoology 44: 863-871.

Nakamura, K. 1977. A model for the functional response of a predator to varying prey densities; Based on the feeding ecology of wolf spiders. Bulletin of National Institute of Agricultural Science (C) 31: 29-89.

Nobel, P. S. 1974. Introduction to Biophysical Plant Physiology. W. H. Freeman and Company, San Francisco. 448 pp.

Ontario Ministry of Agriculture and Food. 2001. Growing Greenhouse Vegetables. Ontario Ministry of Agriculture and Food, Publication Number 371. Queen's Printer, Toronto, Ontario, Canada. 116 pp.

Ramakers, P. M. J. and T. M. O'Neill. 1999. Implementation of IPM: Case Studies - Cucurbits. pp. 435-453 *In* Integrated Pest and Disease Management in Greenhouse Crops. Albajes R., M. Lodovica Gullino, J. C. van Lenteren, and Y. Elad (eds.) Kluwer Academic Publishers, London. 545 pp.

Rott, A. S. and D. J. Ponsonby. 2000. Improving the control of *Tetranychus urticae* on edible glasshouse crops using a specialist coccinellid (*Stethorus punctillum* Weise) and a generalist mite (*Amblyseius californicus* McGregor) as biocontrol agents. Biocontrol Science and Technology 10: 487-498.

Sabelis, M. W. 1981. Biological control of two-spotted spider mites using phytoseiid predators. Part I. Modelling the predator-prey interaction at the individual level. Agricultural Research Reports, Agricultural University, Wageningen. Netherlands. 242 pp.

Sandness, J. N. and J. A. McMurtry. 1972. Prey consumption behavior of *Amblyseius largoensis* in relation to hunger. The Canadian Entomologist 104: 461-470.

SAS Institute, 1995. *SAS/STAT* users guide. SAS Institute. Cary, NC. 1606 pp.

Shipp, J. L. and G. H. Whitfield. 1991. Functional response of the predatory mite, *Amblyseius cucumeris* (Acari: Phytoseiidae), on western flower thrips, *Frankliniella occidentalis* (Thysanoptera: Thripidae). Environmental Entomology 20: 694-699.

Shipp, J. L., K. I. Ward, and T. J. Gillespie. 1996. Influence of temperature and vapor pressure deficit on the rate of predation by the predatory mite, *Amblyseius cucumeris*, on *Frankliniella occidentalis*. Entomologia Experimentalis et Applicata 78: 31-38.

Shipp, J. L. and P. M. J. Ramakers. 2004. Biological control of thrips on vegetable crops. pp. 265-276 *In* Biocontrol in protected culture. Heinz K. M., R. G. Van Driesche, and M. P. Parrella (eds.) Ball Publishing, Batavia, Illinois. 552 pp.

Stenseth, C. 1979. Effect of temperature and humidity on the development of *Phytoseiulus persimilis* and its ability to regulate populations of *Tetranychus urticae* (Acarina: Phytoseiidae, Tetranychidae). Entomophaga 24: 311-317.

Thompson, D. J. 1978. Towards a realistic predator-prey model: The effect of temperature on the functional response and life history of larvae of the damselfly, *Ischnura elegans*. Journal of Animal Ecology 47: 757-767.

van Houten, Y. M. and A. M. M. van Lier. 1995. Influence of temperature and humidity on

the survival of eggs of the thrips predator *Amblyseius cucumeris*. Mededelingen van de Faculteit Landbouwwetenschappen Rijksuniversiteit Gent 60/3a: 879-884.

van Houten, Y. M., P. C. J. van Rijn, L. K. Tanigoshi, P. van Stratum, and J. Bruin. 1995a. Preselection of predatory mites to improve year-round biological control of western flower thrips in greenhouse crops. Entomologia Experimentalis et Applicata 74: 225-234.

van Houten, Y. M., P. van Stratum, J. Bruin, and A. Veerman. 1995b. Selection for non-diapause in *Amblyseius cucumeris* and *Amblyseius barkeri* and exploration of the effectiveness of strains for thrips control. Entomologia Experimentalis et Applicata 77: 289-295.

Zhang, Y, T. J. Jewett, and J. L. Shipp. 2002. A dynamic model to estimate in-canopy and leaf surface microclimate of greenhouse cucumber crops. Transactions of American Society of Agricultural Engineers 45: 179-192.

Zhang, Y. and J. L. Shipp. 2002. Manipulating plant moisture conditions using greenhouse high-pressure fogging. HorTechnology 12: 261-267.

NEW RECORDS FOR *RHOPALOSIPHUM RUFIABDOMINALE* (SASAKI) (HEMIPTERA: APHIDIDAE) ON GREENHOUSE TOMATOES AND PEPPERS

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The rice-root aphid, *Rhopalosiphum rufiabdominale* (Sasaki) (Hemiptera: Aphididae), described from upland rice in 1899 (Doncaster 1956), is known to have a worldwide distribution (Blackman and Eastop 2000). Primary hosts are *Prunus* spp., while secondary hosts are monocotyledonous plants in the families Poaceae and Cyperaceae but include some dicotyledons, especially Solanaceae (Blackman and Eastop 2000). The heteroecious holocycle between *Prunus* and roots of secondary hosts was reported from Japan (Yano et al. 1983; Torikura 1991). Elsewhere, *R. rufiabdominale* is thought to be anholocyclic on roots of secondary hosts. In many parts of the world it is a pest of rice and cereals (Yano et al. 1983; Chapin et al. 2001). *Rhopalosiphum rufiabdominale* is not known to overwinter in Ontario, but migrates annually from the southern United States (Paliwal 1980).

In October 2004, numerous aphids were observed on the roots of greenhouse sweet pepper, *Capsicum annuum* L. (Solanaceae) at the Agriculture and Agri-Food Canada Greenhouse and Processing Crops Research Centre in Harrow, ON. Specimens were identified as *R. rufiabdominale* by E. Maw (Agriculture and Agri-Food Canada, Eastern Cereal and Oilseed Research Centre, Ottawa). The following spring in April 2005, large populations of *R. rufiabdominale* were again observed at the same location, but on this occasion on the lower stem of greenhouse grown tomatoes, *Lycopersicon esculentum* Mill. (cv Rhapsody) (Solanaceae). Identification was confirmed by R. G. Foottit. All plants were infested. The aphids were observed moving up the stem from the root zone and were alate viviparae. Aphids dispersed and disappeared as the season progressed. We believe that the aphids may have overwintered in the greenhouse on secondary hosts as April is too early in the season in Ontario for winged migrants to have arrived from the southern United States. Paliwal (1980) reported *R. rufiabdominale* on cereals from mid-July onwards in Ontario. In late October 2005, large populations of alate *R. rufiabdominale* were observed again on greenhouse tomatoes on the lower stems of the plants at the same location. By late November populations declined and few alates were observed alive on the above ground

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portions of the plants. In this instance, it is probable that winged aphids moved into the greenhouse from outside.

This is the first record of *R. rufiabdominale* on greenhouse tomatoes and sweet pepper in Canada. It has been previously reported causing damage on greenhouse grown zucchini in Italy (Ciampolini et al. 1993). Earlier host records of *R. rufiabdominale* in the Canadian National Collection include *Picea glauca* (roots of spruce seedlings in nursery; Ladner, British Columbia), *Gardenia* spp. (roots; Surrey, British Columbia), *Triticum* spp. (Ottawa, Ontario), and *Sparangium* spp. (Ottawa, Ontario).

Little information is known about the potential damage and yield loss due to *R. rufiabdominale* on greenhouse tomatoes and sweet pepper. However, its overwintering presence in Ontario greenhouses has implications outside the scope of protected cultivation, specifically on cereal crops where its impact has been documented (Jedlinski 1981; Riedell et al. 2003). This aphid is an effective vector of barley yellow dwarf virus (BYDV) in Canada (Paliwal 1980). BYDV is distributed worldwide and is considered one of the most economically important diseases of cereals in the world (Riedell et al. 2003), and can persist in volunteer cereals and wild grasses (Paliwal 1982). BYDV is present in cereal crops in Ontario every year but the incidence varies from one region to another (Paliwal and Comeau 1987). In Illinois, Jedlinski (1981) reported that subterranean *R. rufiabdominale* apterae are capable of overwintering on seedling wheat and transmitting BYDV, and suggested that undetected aphid colonies may explain BYDV outbreaks in the absence of conspicuous aphid populations. However, Chapin et al. (2001) found no correlation between *R. rufiabdominale* abundance and BYDV incidence and yield loss on the coastal plains of south Carolina.

Important aphid vectors of BYDV in Ontario are *R. padi* L., *R. maidis* (Fitch), and *Sitobion avenae* (Fabricius) (Hemiptera: Aphididae), which migrate each year from the United States (Paliwal and Comeau 1987). However, the potential importance of *R. rufiabdominale* should not be overlooked since the transmissibility of BYDV isolates to cereal hosts by *R. rufiabdominale* is similar to *R. padi* (Jedlinski 1981). If *R. rufiabdominale* becomes prevalent in greenhouses, it has the potential to move into cereal fields earlier than other aphid vectors more commonly associated with BYDV in Ontario.

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References

Blackman, R. L. and V. F. Eastop. 2000. Aphids on the World's Crops: an identification and information guide. 2nd edition. John Wiley & Sons, Ltd., Chinchester, UK.

Chapin, J. W., J. S. Thomas, S. M. Gray, D. M. Smith, and S. E. Halbert. 2001. Seasonal abundance of aphids (Homoptera: Aphididae) in wheat and their role as barley

yellow dwarf virus vectors in the South Carolina coastal plain. Journal of Economic Entomology 94: 410-421.

Ciampolini, M., V. di Perna, and C. Maiulini. 1993. Damage by root aphids to vegetable crops in greenhouses in Lazio. Informatore-Agrario 49: 59-63.

Doncaster, J. P. 1956. The rice root aphid. Bulletin of Entomological Research, 47: 741-747.

Jedlinski, H. 1981. Rice root aphid, *Rhopalosiphum rufiabdominalis*, a vector of barley yellow dwarf virus in Illinois, and the disease complex. Plant Disease 65: 975-978.

Paliwal, Y. C. 1980. Transmission of barley yellow dwarf virus isolates by the cereal root aphid *Rhopalosiphum rufiabdominalis*. Canadian Journal of Plant Pathology 2: 90-92.

Paliwal, Y. C. 1982. Role of perennial grasses, winter wheat, and aphid vectors in the disease cycle and epidemiology of barley yellow dwarf virus. Canadian Journal of Plant Pathology 4: 367-374.

Paliwal, Y. C and A. Comeau. 1987. Yellow dwarf of cereals. Ontario Ministry of Agriculture Food and Rural Affairs Factsheet 87-074. http://www.omafra.gov.on.ca/english/crops/facts/87-074.htm. Last accessed 6 January 2006.

Riedell, W. E., R. W. Kieckhefer, M. A. C. Langham, and L. S. Hesler. 2003. Root and shoot responses to bird cherry-oat aphids and barley yellow dwarf virus in spring wheat. Crop Science 43: 1380-1386.

Torikura, H. 1991. Revisional notes on Japanese *Rhopalosiphum* with keys to species based on morphs on the primary host. Japanese Journal of Entomology 59: 257-273.

Yano, K., T. Miyake and V. F. Eastop. 1983. The biology and economic importance of rice aphids (Hemiptera: Aphididae): a review. Bulletin of Entomological Research 73: 539-566.

BOOK REVIEW

For Love of Insects. 2003. *by* T. Eisner. Harvard University Press, Cambridge, USA. 448 pp + xi. ISBN 0-674-01827-3 (paperback edition: 2005). $19.95 US.

"This book is about the thrill of discovery." Thus begins For Love of Insects. It is a book on the wonder of insects, focusing primarily on insect chemicals in an ecological context. Eisner has strung together stories from a career's worth of research. The stories are divided by subject into chapters such as, "Tales from the Website," on spider webs and "The Circumventers," on defensive chemicals. By reading this collection of related stories, the reader not only learns about the specific systems discussed, but also gains a general appreciation for the role of chemicals in insect ecology. What is most impressive is that Eisner has made the book accessible, thought provoking, and a true joy to read without sacrificing any scientific accuracy.

Eisner is a rare breed, becoming increasingly rarer: a highly successful naturalist who is equally skilled in the field and laboratory. Exploratory walks in the field draw his attention to curiosities: Why don't fish eat whirligig beetles? What kind of insect eats carnivorous plants? Inspired, he then conducts experiments in the laboratory to answer his questions, often using elegantly simple methods. He is quick to give credit to colleagues contributing to discoveries. Even his pet bird, Phogel, gets credit for telling Eisner which insects were palatable.

Eisner's insect stories are fascinating, thanks in part to his storytelling ability and of course in large part to the insects themselves. There are walking sticks that preemptively spray avian predators before being pecked. There are *Eleodes* beetles that assume a handstand defensive posture, exposing their chemical-packed abdomen, and *Moneilema* beetles that mimic this posture. There is a dizzying complex of six beetle and four moth species, all mimicking various morphs of each other, varying in habitat, and even preying upon each other in some cases. More questions than answers are available for this system in particular, and Eisner encourages future research with the words "doctoral students take note."

The most interesting section outlines Eisner's research on moths of the genus *Utetheisa*. Over the course of five PhD students' research programs, Eisner's lab has been able to compile a thorough account of their life history, from larval food choice to defensive chemicals to sexual selection to cannibalism. Each time I thought the story was as intricate as it could be, more discoveries were revealed that were even more exciting. Eisner anticipates the reader's mind throughout, and asks aloud the very questions you want to ask.

One of the best aspects of this book is its photographs. They often tell stories better than any text can. The spray of bombardier beetles, for instance, can be summed up in just a few pictures. Small diagrams of relevant chemical structures are provided, but are bonus material, not necessary for a reader's understanding of a story. Photographs augment almost every subject of this book, from scanning electron micrographs of ant appendages tangled up with polyxenid millipede tufts, to dissection images that illustrate how antlions avoid eating ant acid sacs. Not only are the photographs beautiful and informative, but they also allow the reader to simply flip through the pictures in the book years after reading to

jog memory of the book's content. If your memory is as poor as mine, you will find this a great benefit.

Although Eisner cares deeply about conservation, he does not focus on it directly. Instead he endeavours to share his wonder of insects with an implied message: if you understand the wonder of nature you will care enough to protect it. It is no coincidence that the chemical structure of Mexican bean beetle defense appears in the final few pages of the book; its elaborate ring structure will impress anyone regardless of chemistry knowledge. These ant-deterrent compounds were previously undiscovered, and Eisner drives home the point that much knowledge can be gained from nature.

My only criticism of the book is a small one. Although the order and family is mentioned for many of the species in this book, it is not given for all. A standard "(Order, Family)" accompanying the first mention of each species would encumber readability little, and would help those readers interested in taxonomic classification.

I strongly recommend this book to any reader curious about insect adaptations. The writing is accessible enough that inquisitive members of the public can enjoy the book. Researchers young and old will appreciate not only the scientific content of the book, but also Eisner's approach to science itself. He combines non-hypothesis-driven observations with "biorationality" logical deductions to derive hypotheses, and then tests them with elegantly simple experiments. He freely offers suggestions of promising areas for future research. He includes some unpublished results, such as how stink bugs' saliva weakens spider webs to facilitate escape. If there is any one thing that encompasses the sentiment of this book, it is punctuation. Question marks are abundant. Wonder is abundant in this book, as in nature.

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2005 ANNUAL MEETING

The **142nd Annual Meeting** of the **Entomological Society of Ontario** was held at the University of Toronto on October 21-23, 2005. Approximately 80 people attended the meeting, which had the theme of "Insects in the Urban Environment". The Entomological Society of Ontario thanks all the speakers, participants, and organizers who helped to make the meeting such a success. The Entomological Society of Ontario is grateful for the support received from Ontario Ministry of Natural Resources (Forest Health & Silviculture Section), Engage Agro, Landscape Ontario, Lareseco, Faculty of Forestry, University of Toronto, BASF, N.M. Bartlett Inc., Syngenta Crop Protection Canada, and the Toronto Zoo.

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